


# Environmental analysis of a potential district heating network powered by a large-scale cogeneration plant

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**Abstract** Among the solutions for the achievement of environmental sustainability in the energy sector, district heating (DH) with combined heat and power (CHP) systems is increasingly being used. The Italian city of Turin is in a leading position in this field, having one of the largest DH networks in Europe. The aim of this work is the analysis of a further development of the network, addressed to reduce the presence of pollutants in a city that has long been subject to high concentration levels. The environmental compatibility of this intervention, especially in terms of nitrogen oxides (NO<sub>x</sub>) and particulate matter (PM) emissions, is evaluated. The pollutants dispersion is estimated using the CALPUFF model. The forecasting scenario is created

firstly by simulating the energy production of the main generation plants in response to the estimated heat demand, and secondly by investigating the amount and the dispersion of pollutants removed due to the elimination of the centralized residential heaters. The results show a future reduction in ground level average NO<sub>x</sub> concentration ranging between 0.2 and 4 μg/m<sup>3</sup>. The concentration of PM remains almost unchanged. Measures are then taken to lower the uncertainty in the simulation scenarios. This study provides important information on the effects of a change of the energy configuration on air quality in an urban area. The proposed methodological approach is comprehensive and repeatable.

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- Assessment of the local impacts of the potential district heating network is performed.
  - The energy balance of a future scenario is defined and compared to the present.
  - Dispersion of NO<sub>x</sub> and TSP is calculated and represented by iso-concentration maps.
  - The results quantify and locate the average improvement on air quality.
  - Additional consideration is made on the contribution of single pollution sources.

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In memory of Professor Giuseppe Genon

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**Keywords** District heating · Air pollution · Environmental compatibility · NO<sub>x</sub> · Particulate matter · Pollutant dispersion model

### Abbreviations

DH	District heating
CHP	Combined heat and power
NO <sub>x</sub>	Nitrogen oxides
PM	Particulate matter
TSP	Total suspended particulate
CC	Combined cycle
CEMS	Continuous emission monitoring system

### Introduction

District heating (DH) 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). Among the most frequent plant configurations, the combined cycle (CC) units fueled by natural gas are identified. These systems allow the achievement of high conversion efficiency, thanks to the simultaneous production of heat and electrical energy (Lund et al. 2014). The environmental analysis of generation plants connected to DH networks is crucial, as these are usually located in heavily populated urban areas, thus characterized by the combined contributions of different emission sources, such as traffic, industrial, and residential activities.

District heating is a technology used for supplying a town district or a complete town with the heat generated in large production plants. By concentrating and scaling up the heat production instead of using single house boilers, a lower specific heat production cost can be obtained as well as a higher conversion efficiency and the possibility to co-generate electricity. District heating networks are commonly proposed in previous works as an environmentally friendly solution for providing heating services for the built environment due to their multiple benefits, such as centralized heat, production located outside urban centers, possible utilization or renewable heat sources and increased comfort for the consumers. Currently, there are about 6000 district heating networks operating in Europe with an overall length of 200,000 km (Connolly et al. 2014). Considering the scarcity of these systems in Europe, previous publications suggested their opportunity of expansion (Colmenares-Santos et al. 2016).

By analyzing the existing scientific production, many works concerning different aspects of DH are found. Vesterlund et al. (2016) applied a simulation tool developed in MATLAB/Simulink in order to analyze the flow distribution in the DH network of the town of Kiruna (Sweden).

Andrić et al. (2016) developed an emergy approach to infer environmental performance of the heat provided by DH networks, considering two types of DH systems: ESPEX (four-pipe network) and traditional two-pipe DH network.

Lake et al. (2017) showed the implementation of district heating and cooling systems across a broad set of case studies previously reported in papers. Topics addressed include their history, system identification, energy sources, design considerations, environmental impact, economic feasibility, performance analysis, and the role of energy policy.

Bach et al. (2016) analyzed the integration of large-scale heat pumps in DH systems in Copenhagen.

From the environmental point of view, numerous studies have been conducted on nitrogen oxides (NO<sub>x</sub>) and particulate matter (PM) local emissions associated with the operation of cogeneration plants for DH. Such studies often use dispersion models for the calculation of the concentration of pollutants at ground level. The results reported can differ, depending on the size of the plant, the type of fuel, and the operating conditions. Among the publications, a study by Brattebø and Reenaas (2012), conducted on a waste to energy cogeneration plant, shows an increased NO<sub>x</sub> emissions compared to an alternative scenario for waste management, as well as the need for advanced abatement technologies. Genon et al. (2009) analyzed the local impact of a future small DH system fueled by natural gas engines. Their study considered two cases where 22 and 105 residential heaters were replaced with a CHP and DH system. The results indicated that the NO<sub>x</sub> emissions may in some cases exceed the existing emissions, although this aspect is strongly related to the type of conversion facility considered. A second study by Torchio et al. (2009) developed the study by Genon et al. (2009), showing a reduction of PM concentration for the DH system connected to the 105 buildings. Recently, Torchio (2015) proposed an environmental and economic comparison of three different options: district heating, distributed generation, and separate production of heat and power. The results for district heating option showed that the systems driven by microturbines and fuel cell technologies lead to a reduction of NO<sub>x</sub> emissions, while internal combustion engines did not show a local NO<sub>x</sub> saving. Similar results are confirmed by a study by Haichao et al. (2013).

The aim of this work is the evaluation of the environmental compatibility of intervening to expand the DH network in the urban area of Turin, in terms of local impact of NO<sub>x</sub> and PM.

The Turin metropolitan area is currently in a leading position in the DH sector, having one of the largest networks in Europe. 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, removing

centralized residential heaters. The characterization of emissions should be conducted both at the global level, namely by assessing the overall contribution to the greenhouse effect, and at the local level, identifying potentially harmful pollutants and studying their dispersion in the territory (Ravina and Genon 2015). Among the most important pollutants present at the local level,  $\text{NO}_x$  and PM are of paramount interest, as these substances are harmful to human health and ecosystems (Singh et al. 2016; Liora et al. 2016).

## Methodology

Local environmental impacts of  $\text{NO}_x$  (as equivalent  $\text{NO}_2$ ) and PM (as total suspended particulate, TSP) were studied for a 1-year period. To this end, current emission scenario was analyzed and a feasible energy and emission configuration was developed.

The first step was defining the energy balance in the study area. The flow of pollutants emitted by the sources was then estimated, and their dispersion was simulated implementing the CALPUFF dispersion model (US EPA 2011). The latest available (related to 2014) power units emission flow rates were used in this study; however, the meteorological input datasets collected in 2010 were used, because sufficiently accurate and complete datasets were not available for 2014. However, average meteorological conditions in the period

2010–2014 in the study area were quite similar, so the approximation introduced is negligible.

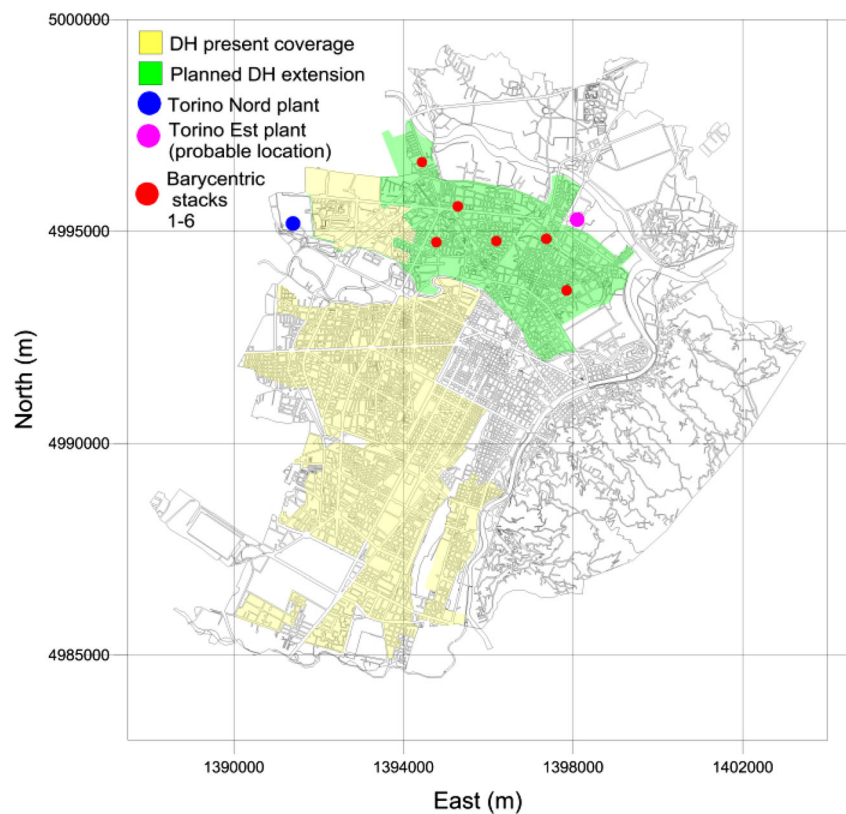
The following paragraphs describe the area of study, the simulation process of the present and future energy and emission scenario, and how the CALPUFF model was set up and used.

## Area of study

The potential development of the Turin DH network covers the area reported in Fig. 1, which includes four districts of the northern and eastern parts of the city. The residential volume currently served by the DH network amounts to about 57 million  $\text{m}^3$ , corresponding to approximately 570,000 inhabitants. The total extension of the network amounts to 527 km. The development project involves approximately a further 20 million  $\text{m}^3$ . The thermal energy for this extra part of network is supplied by the Torino Nord (TO-N) plant, consisting of the following:

- A combined cycle (CC) cogeneration unit fueled by natural gas
- Four auxiliary boilers for integration and reserve, producing 85 MW each, fueled by natural gas
- A heat storage system consisting of 6 batteries with a total capacity of about 5000  $\text{m}^3$
- A system for pumping, pressurization, expansion, and replenishing of the water in the DH network

**Fig. 1** Current and planned extension of the DH network in the urban area of Turin. Location of the emission sources considered in the study. Coordinates system is UTM ED50 32T



Main technical data of the generation units are reported in Table 1. Surface, volume, and characterization of heating system (type of fuel, centralized, or autonomous heating) data related to buildings in the study area were obtained from the 2001 Italian Census (Istat 2001). The data were extracted and processed using the Quantum GIS application (QGIS 2016).

**Present scenario (year 2014)**

The present emission scenario was developed considering the combined contribution of the TO-N plant in its actual operating mode, and the residential area subject to the DH network extension. As a first step, the energy balance of each source was defined. Then, the emission flow of pollutants was calculated by applying the emission factors.

For the characterization of the TO-N plant, two point emission sources were considered, one for the main stack of the CC unit and another for the four auxiliary boilers. This corresponds to the real plant configuration, since the four stacks of the boilers can be considered as a single stack. Thermal energy produced by main generation unit and auxiliary boilers was calculated starting by hourly thermal power transferred to the DH network ( $E_{tr}$ ) that is directly measured by the continuous emissions monitoring system (CEMS) installed on the plant (Iren Energia 2014a). The selected year was 2014, as it represents the latest dataset available. Thus, the thermal energy produced by the boilers  $E_{cald}$  was calculated by difference as:

$$E_{cald} = E_{tr} - E_{tonmax} \quad \text{if } E_{tr} > E_{tonmax} \quad (1)$$

$$E_{cald} = 0 \quad \text{if } E_{tr} < E_{tonmax} \quad (2)$$

where  $E_{tonmax}$  is the maximum thermal energy that can be transferred to the DH exchanger, namely 220 MWh.

The flow of  $NO_x$  emitted by the CC unit was also directly extracted by the CEMS.  $NO_x$  emissions of auxiliary boilers were calculated by multiplying  $E_{cald}$  for the average emission factor declared by plant operator for the year 2014 (Table 2). TSP flow was instead calculated by applying EMEP/EEA emission factors (Table 2).

For the characterization of the emission flows of residential sources subject to the DH network extension, six homogeneous areas were defined, considering different types of buildings (period of construction, geometry) and population density. A barycentric stack was assigned to each area (Fig. 1). Heat demand of buildings was calculated by applying the model proposed by Fracastoro and Serraino (2011), in which data of surface, number of floors, type of fuel (natural gas, diesel oil, LPG, or heavy oil), and type of system (centralized or autonomous) are considered. This energy model returned the annual thermal energy need of single buildings. The annual figure was then multiplied by the hourly distribution of a benchmark building, i.e., using the real-time demand curve of a representative building, which is located in Turin and subject to a continuous measurement. Hourly thermal energy request was then multiplied by the corresponding emission factor (Table 2).

**Future scenario**

Future scenario was developed considering the connection to the DH network of the only buildings with centralized heating, considering an average commercial penetration factor. Annual thermal energy consumption of the six areas was then divided

**Table 1** Technical data of the main components of the TO-N plant (modified from Jarre et al. 2016)

Component	Value	Torino Nord plant
Gas turbine	Gross nominal electrical power (MW)	270
	Fuel	Natural gas
Steam generator for the thermal recovery (high/medium/low pressure stages)	Pressure (bar)	125/30/4.5
	Temperature (°C)	550/550/237
Steam turbine	Gross nominal electrical power (MW)	119
District heating heat exchangers	Nominal thermal power	220
	Inlet temperature (°C)	70
	Outlet temperature (°C)	120
Condenser	Cooling fluid	Air
Combined cycle operation (ISO conditions on site)	Net electric power (MW)	390
	Global efficiency (–)	56%
Combined cycle + cogeneration operation (ISO conditions on site)	Thermal power (MW)	220
	Global efficiency (–)	87%

**Table 2** Emission factors of NO<sub>x</sub> and TSP

Emission source	NO <sub>x</sub> emission factor (kg/MWh)	TSP emission factor (kg/MWh)
Torino Nord—combined cycle	0.167 <sup>1</sup>	5.55·10 <sup>-5</sup> <sup>2</sup>
Torino Nord—auxiliary boilers	0.063 <sup>3</sup>	2.47·10 <sup>-4</sup> <sup>4</sup>
Torino Est	0.063	2.47·10 <sup>-4</sup>
Residential stacks (natural gas)	0.180	1.62·10 <sup>-3</sup>
Residential stacks (diesel oil)	0.180	5.4·10 <sup>-3</sup>
Residential stacks (LPG)	0.180	5.4·10 <sup>-3</sup>
Residential stacks (heavy oil)	0.540	1·10 <sup>-1</sup>

<sup>1</sup> Source: Iren Energia (2014a)<sup>2</sup> Source: EMEP/EEA (2013)<sup>3</sup> Source: Iren Energia (2014b)

into a portion connected to DH ( $E_{\text{fut\_ttr}}$ ) and a portion not connected to DH ( $E_{\text{fut\_nottr}}$ ):

$$E_{\text{fut\_ttr}} = E_{\text{cen}} \cdot F_p \quad (3)$$

$$E_{\text{fut\_nottr}} = E_{\text{cen}} \cdot (1 - F_p) + E_{\text{aut}} \quad (4)$$

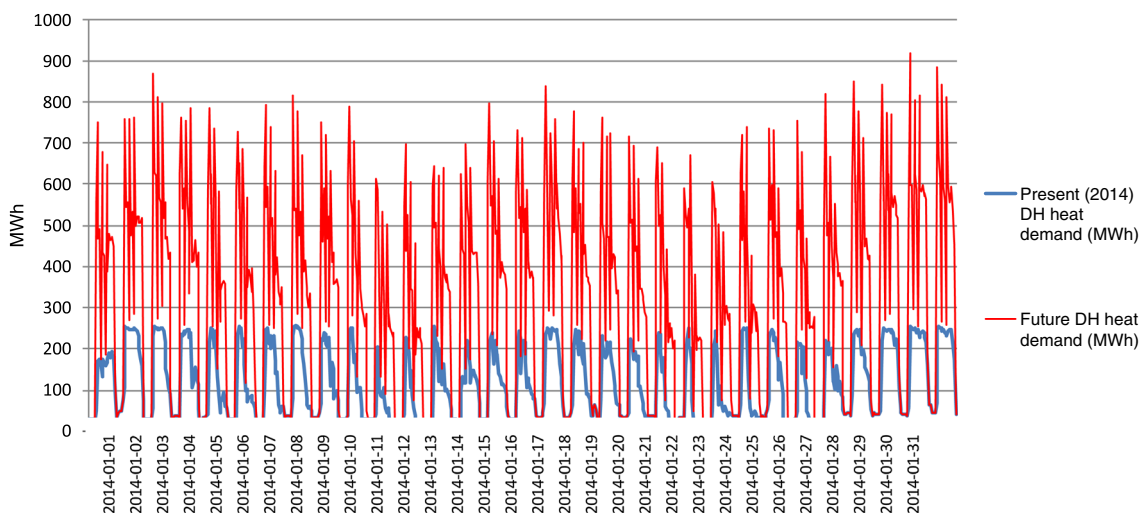
where  $E_{\text{cen}}$  is the thermal energy requirement of buildings with centralized heating system,  $F_p$  is the average commercial penetration factor of 0.8 (Province of Turin, 2009), and  $E_{\text{aut}}$  is the thermal energy requirement of the buildings with an autonomous heating system.  $E_{\text{fut\_ttr}}$  and  $E_{\text{fut\_nottr}}$  were then distributed on an hourly basis using the aforementioned methodology. The term  $E_{\text{fut\_ttr}}$  was subsequently added to the current demand  $E_{\text{tr}}$ , obtaining the required hourly thermal energy to be satisfied in the future operational mode ( $E_{\text{fut\_tot}}$ ):

$$E_{\text{fut\_tot}} = E_{\text{fut\_ttr}} + E_{\text{tr}} \quad (5)$$

$E_{\text{tr}}$  and  $E_{\text{fut\_tot}}$  terms in the month of January are reported in Fig. 2. Peak values of  $E_{\text{fut\_tot}}$  reach around 900 MWh, going

beyond the operational capacity of the TO-N plant and its auxiliary boilers (220 MWh + 340 MWh). For this reason, it was necessary to simulate the entry into service of a new integration and reserve system, able to satisfy the residual heat demand during peak hours. This system was identified in the Torino Est (TO-E) plant, a new generation group consisting of 4 integration boilers having a nominal thermal power of 85 MW each, technically identical to those of the TO-N plant. Indeed, to date, there are feasibility studies in progress for the construction of this plant that also identify a possible location in the area (Fig. 1; Turin Province 2009).

Assuming the operation of the TO-E plant, the future configuration of energy production was defined. The following heat dispatching priority was assumed: TO-N (combined cycle); TO-E; TO-N (auxiliary boilers). Hourly production curves of the three generation units were finally multiplied by the corresponding emission factors, obtaining hourly emission flows of NO<sub>x</sub> and TSP. TO-E plant emission factors were assumed equal to those of TO-N auxiliary boilers (Table 2).



**Fig. 2** Hourly thermal power demand of the DH network in northern and eastern areas of Turin for the year 2014 (present scenario) and for future scenario, month of January

**Environmental balance**

The environmental balance of NO<sub>x</sub> and TSP emissions was obtained by calculating the average concentration differences at ground level resulting from CALPUFF simulations. As previously reported, the present scenario considered the combined contribution of the TO-N plant and buildings not connected to the DH network. The future scenario considered the combined effect of the TO-N and TO-E plants, and buildings still not connected to DH after the intervention of extension.

To simulate the dispersion of NO<sub>x</sub> and PM in the scenarios considered, geophysical and meteorological input data were obtained from the Regional Agency for Environmental Protection of the Piedmont Region (ARPA). Meteorological data included wind and temperature analyzed fields from the European Centre for Medium Range Weather Forecast (ECMWF), two radiosoundings (located outside the computational domain), and 14 surface stations. These data were used by ARPA to reconstruct 3D wind and temperature fields on an hourly basis, implementing the MINERVE diagnostic model (ARIA Technologies 2001). The completeness and availability of the data were assessed; the year used for driving the simulations was 2010. The complete list of weather and geophysical variables used as model input is reported in Table 3.

Weather and orographic data covered a domain of 100 × 100 km<sup>2</sup> with a horizontal resolution of 1000 m. The same grid represented also the modeling domain. The domain extension was wider than the expected extension of dispersion impacts. This was done to consider the meteorological features of the area because the surrounding orographic reliefs may indirectly affect the dispersion. The creation of an algorithm in Fortran programming language was necessary to convert data into a compatible format to the CALPUFF model. The key parameters of the emission sources used in the simulations are reported in Table 4. The simulation was run on the entire heating season of the year, i.e., from October to March.

*CALPUFF model and settings*

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

modeling system consists of three main components and a set of preprocessing and post-processing programs. The main components of the modeling 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 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 modeled sources, reproducing dispersion and transformation processes along the way. Temporal and spatial variations in the meteorological fields selected 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, identifying the highest and second highest 3-h average concentrations at each receptor, for example. For more technical details on the CALPUFF model structure, see the user’s guide (US EPA 2011).

The model settings for the base case simulation were the following:

- Chemical transformation scheme: MESOPUFF II (Scire et al. 1984). The transformation processes included in the MESOPUFF II mechanism are the conversion of sulfur dioxide to sulfate and of nitrogen oxides to nitrate aerosol. These processes include photochemical reactions which transformation rates are expressed as a function of ozone concentration in air. For this reason, hourly measurements of ozone concentration taken by the monitoring station located in Via della Consolata, Turin, had to be introduced to the model.
- Building the downwash method: ISC method (Huber and Snyder 1976).
- Building profile for downwash calculation: buildings 15 m high and 15 m wide, spaced every 10°. This profile is consistent with the real building density in most of the sub-areas analyzed in the study; it simulates a dense urban structure and was chosen to evaluate the worst conditions from the emissive aspect.
- Plume rise calculation method: Briggs (1982).

**Table 3** List of geophysical and meteorological input variables for CALPUFF dispersion model

Meteorological data	Geophysical data
u, v, and w wind components; air temperature; surface friction velocity; convective velocity scale; mixing height; Monin-Obukhov length; PGT stability class; precipitation rate; air density; air temperature; short-wave solar radiation; relative humidity; precipitation type	Surface roughness lengths, land use categories, terrain elevations, leaf area indices

**Table 4** Emission source parameters implemented in CALPUFF model

Source ID	Description	East coord. (km) <sup>6</sup>	North coord. (km) <sup>6</sup>	Height (m)	Diameter (m)	Average exhaust gases temperature (K)	Average exhaust gases speed (m/s)
TO-N1	Torino Nord—combined cycle	1390.95	4995.64	60 <sup>1</sup>	6.0 <sup>1</sup>	274 <sup>4</sup>	Variable <sup>5</sup>
TO-N2	Torino Nord—auxiliary boilers	1390.98	4995.56	60 <sup>1</sup>	8.0 <sup>1</sup>	274 <sup>4</sup>	11.8 <sup>1</sup>
TO-E1	Torino Est	1398.36	4995.21	60 <sup>2</sup>	8.0 <sup>2</sup>	274 <sup>2</sup>	11.8 <sup>2</sup>
TO-A1	Bar. stack area 1	1394.42	4996.94	15 <sup>3</sup>	0.8 <sup>7</sup>	270 <sup>7</sup>	5.0 <sup>7</sup>
TO-A2	Bar. stack area 2	1394.09	4995.44	15	0.8	270	5.0
TO-A3	Bar. stack area 3	1395.20	4995.07	15	0.8	270	5.0
TO-A4	Bar. stack area 4	1396.31	4995.21	15	0.8	270	5.0
TO-A5	Bar. stack area 5	1397.34	4994.29	15	0.8	270	5.0
TO-A6	Bar. stack area 6	1397.36	4993.00	15	0.8	270	5.0

<sup>1</sup> project data, <sup>2</sup> assumed to be equal to Torino Nord auxiliary boilers, <sup>3</sup> average building height extracted from Census data (Istat 2001), <sup>4</sup> assumed to be equal to the Moncalieri plant, for which the data of the CEMS is available, <sup>5</sup> calculated on an hourly basis from the datum of flow of exhaust gases from the stack, <sup>6</sup> reference system ED50 UTM 32N, <sup>7</sup> average data found in previous studies

- Stack tip downwash calculation method: Briggs (1973).
- Method for the calculation of horizontal and vertical dispersion: from internally calculated coefficients using micrometeorological variables. (US EPA 2011).

Once completed the base case simulations, additional model runs were set up with the aim of evaluating the uncertainty of results. The building downwash configuration and the height of barycentric stacks were modified, and the environmental balance was re-calculated. Other simulations were also run by substituting barycentric point sources with area sources.

Output data from CALPUFF were sent to CALPOST post-processor, obtaining hourly concentration grids. Subsequently, the creation of an algorithm in GNU Octave

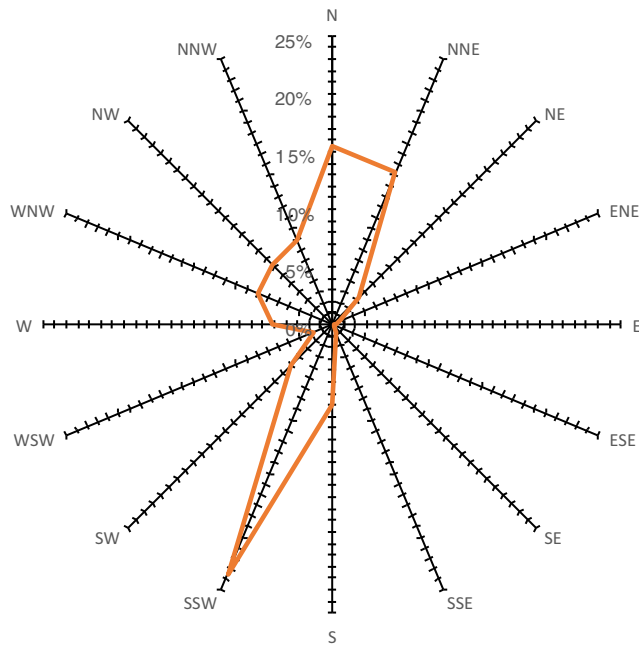
allowed the extraction and localization of the maximum and minimum values, the definition average monthly concentration grids, and the reformatting of data in the form of concentration maps.

## Results

The overall environmental balance of the intervention considered, comparing the present and future annual mass flow of NO<sub>x</sub> and TSP, is reported in Table 5. The concentration maps resulting from the simulation of pollutants dispersion are reported in Figs. 4 and 5. To qualitatively estimate the model performance, the average wind frequency diagram for the heating period considered is reported in Fig. 3. This diagram

**Table 5** Changes in total NO<sub>x</sub> and TSP emission between present (year 2014) and future scenario

Emission source	NO <sub>x</sub> (t/year)		TSP (t/year)	
	Present	Future	Present	Future
TO-N plant	57.68	104.70	0.578	1.078
TO-E plant	–	62.55	–	1.113
Buildings not connected to DH	172.47	57.49	2.497	0.715
Buildings connected to DH (avoided emissions)	–	114.98	–	1.781
Total produced emissions	230.15	224.74	3.075	2.906



**Fig. 3** Average distribution of wind direction frequencies in Turin over the six coldest months of 2010 (October to March)

was constructed extracting hourly data of wind direction by a representative weather station located in Turin. The results of Table 5 show that the extension of the DH network would bring a reduction on total NO<sub>x</sub> emissions of around 5.4 t/year, corresponding to 2.3% of actual emission. For TSP, the reduction would be around 0.17 t/year, corresponding to 5.5% of actual emission.

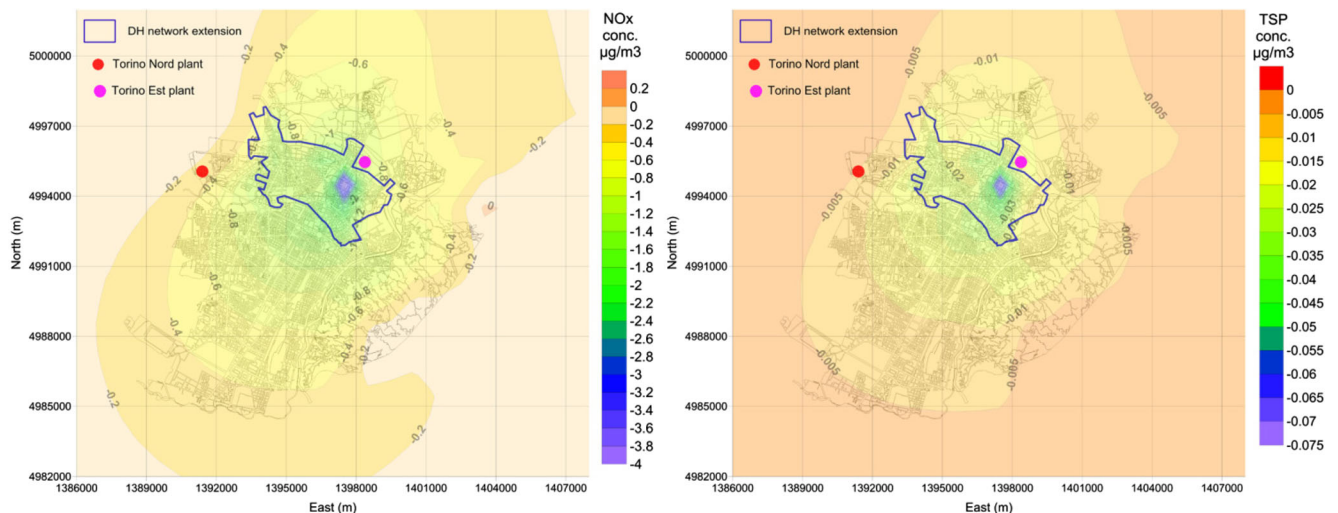
The concentration values were obtained by simulating the aforementioned emission sources. The result of the environmental balance, in terms of NO<sub>x</sub> and TSP average concentration difference at ground level in the urban area of Turin, base case simulation, is shown in Fig. 4. The same result, extended

to the entire modeling domain, is reported in Fig. 5. Positive and negative values indicate increased or reduced impacts, respectively, compared to the present situation. The result shows from 0.2 to μg/m<sup>3</sup> to 4 μg/m<sup>3</sup> reduction of NO<sub>x</sub> concentration with respect to the present situation. Figure 5 indicates that local effects are mainly limited to the urban area and the concentration difference approaches zero in the surrounding. A more detailed description of these results is reported in Appendix A, where the single contribution of generation plants and residential area is reported, as well as positive and negative contributions in future scenario.

The result of TSP dispersion indicates a negligible reduction of the concentration, limited to around 10<sup>-2</sup> μg/m<sup>3</sup>. TSP emission flows are relatively low compared to NO<sub>x</sub>, both in CC plants fueled by natural gas, and in residential centralized systems (TSP emission factors are 2 to 4 order of magnitudes lower than NO<sub>x</sub> emission factors, Table 2).

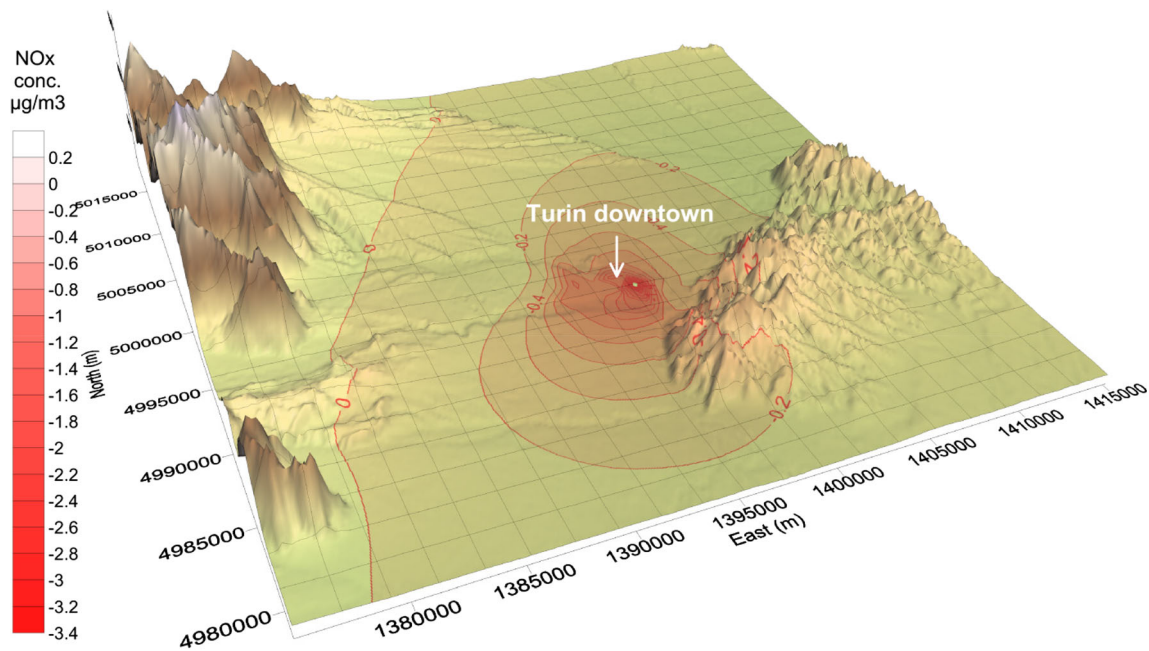
The absolute maximum and minimum values extracted by the GNU Octave algorithm are reported in Table 6 and Table 7. These tables show the occurrence of peak concentrations which shift significantly from the average values. Peak concentrations are influenced by both pollutant emission rate and dispersion conditions. Maximum (positive) values are the effect of the pollutant plume emitted by TO-N and TO-E plants that impact on the hilly areas surrounding Turin. Minimum (negative) values are recorded in the area interested by the DH network extension and result from the impact at ground of low residential stacks emissions.

Additional simulations were run with the aim of characterizing the uncertainty of results. Concentration differences were calculated for NO<sub>x</sub>, considering only the month of January and modifying two model settings: the building downwash configuration and the height of the barycentric stacks representing residential emissions. These two were



**Fig. 4** NO<sub>x</sub> (left) and TSP (right) average concentration difference at ground level between future and present scenario in the urban area of Turin, base case simulation. The average is calculated over the six coldest months of the year (October to March)





**Fig. 5** NO<sub>x</sub> average concentration difference at ground level between future and present scenario in the entire modeling domain. The average is calculated over the six coldest months of the year (October to March)

considered as key factors because building density and profiles in the areas of study are variable, depending on the period of construction. The study area contains in fact districts constructed in different periods of the urban development. The building downwash configuration was modified to simulate two different densities compared to the base case: the “higher and less dense” profile, characterized by 30-m high and 15-m wide buildings, spaced every 20°, and the “less dense” profile, characterized by 15-m high and 15-m wide buildings, spaced every 20°. The result of the environmental balance for the “higher and less dense” profile is reported in Fig. 6. This figure shows a higher concentration difference with respect to the base case (Fig. 4), indicating that the higher and denser is the urban structure, the more pronounced is the downwash effect, i.e., the concentration of pollutants at ground level increases. The result of the “less dense” profile does not differ from the base case simulation. The result of the NO<sub>x</sub> environmental balance calculated modifying the height of barycentric stacks to 30 m is reported in Fig. 7. As expected, the concentration difference is lower compared to the base case,

indicating a maximum reduction of 2.1 μg/m<sup>3</sup>. Figure 7 also shows that the effects of NO<sub>x</sub> dispersion interest a larger area compared to the base case.

As a final step, the base case simulation was reproduced calculating the emissions of the six residential areas using an area source instead of a point source type. The result of the heating season average is reported in Fig. 8. It can be concluded from Fig. 8 that the contaminant removal is more dispersed over the area in comparison with point source simulations.

## Discussion

The results show a general reduction of NO<sub>x</sub> and TSP presence in the urban area of Turin following the DH network extension. This reduction is driven by a connection of the following factors:

- Lower overall emissions (Table 5)

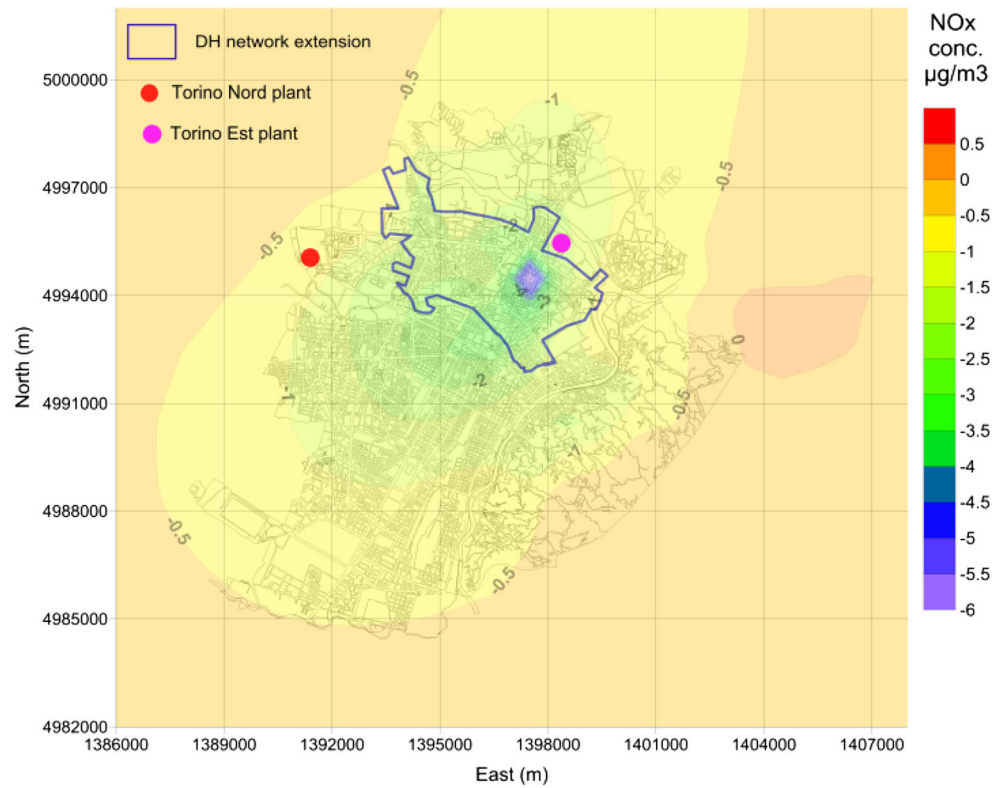
**Table 6** Maximum values of ground level concentration with relative date and position extracted from the simulation of the future scenario

NO <sub>x</sub> maximum conc. (μg/m <sup>3</sup> )	TSP maximum conc. (μg/m <sup>3</sup> )	Month/day/time	East coord. (km)	North coord. (km)
63	0.07	02/06 07:00	1403.500	4993.500
59	0.07	01/31 07:00	1401.500	4989.500
50	0.06	01/31 07:00	1400.500	4989.500

**Table 7** Minimum values of ground level concentration with relative date and position extracted from the simulation of the future scenario

NO <sub>x</sub> minimum conc. (μg/m <sup>3</sup> )	TSP minimum conc. (μg/m <sup>3</sup> )	Month/day/time	East coord. (km)	North coord. (km)
-270	-5.0	12/04 15:00	1397.500	4994.500
-220	-4.0	12/22 11:00	1397.500	4994.500
-212	-3.9	01/09 12:00	1397.500	4994.500

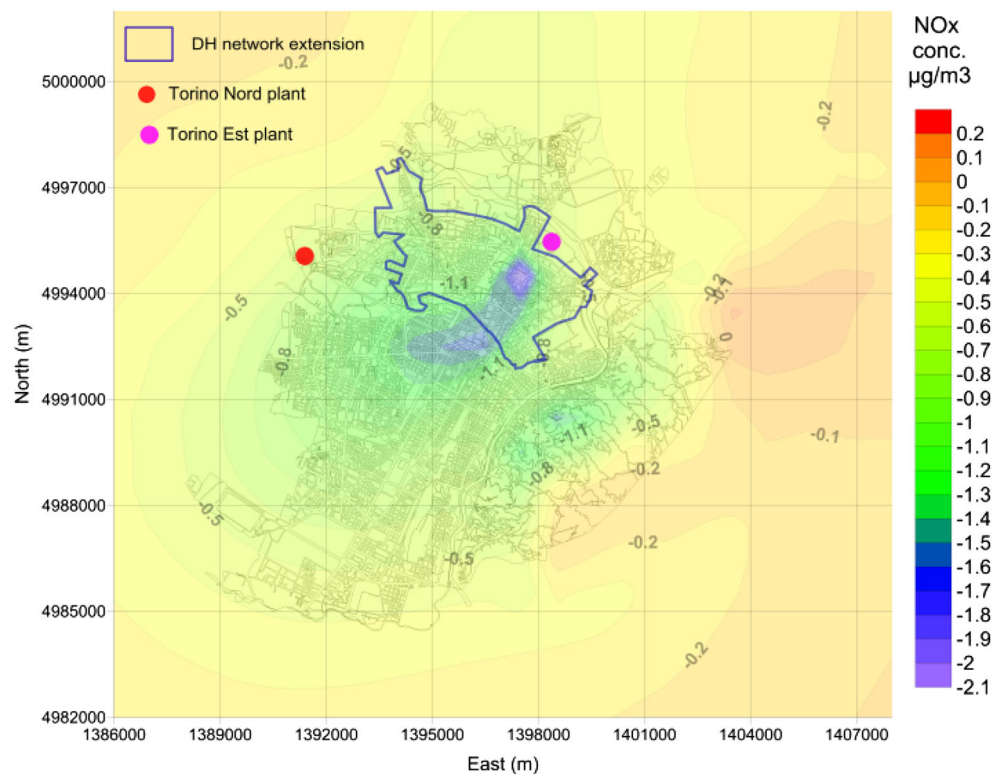
**Fig. 6** NO<sub>x</sub> average concentration difference at ground level between future and present scenario in the urban area of Turin, month of January, with modified settings of the building profile around the emission sources (buildings 30 m high and 15 m wide, spaced every 20°)

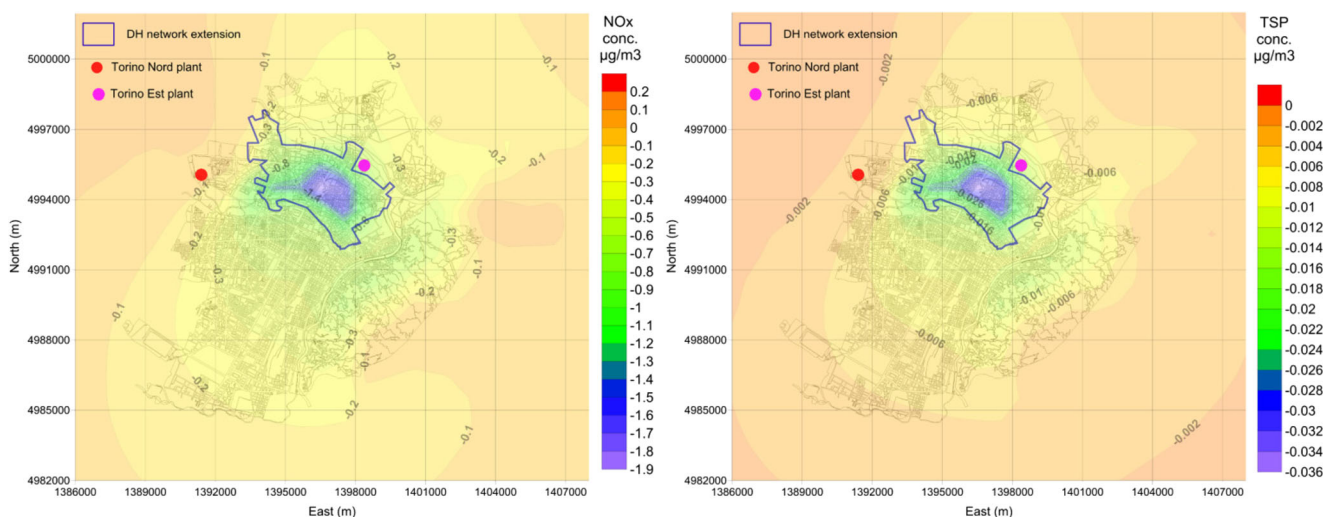


- Higher elevation of the emission sources, corresponding to a greater dispersion of the pollutants' plume
- Greater distance between emission sources (power units) and the receptor sites (residential areas)

To evaluate the order magnitude of the concentration decrease, the reference monitoring stations in the study area (Torino Rebaudengo and Torino Consolata) were considered. The annual average concentration measured by these stations

**Fig. 7** NO<sub>x</sub> average concentration difference at ground level between future and present scenario in the urban area of Turin, month of January, with modified height of the emission sources of the residential areas (30 m)





**Fig. 8** NO<sub>x</sub> (*left*) and TSP (*right*) average concentration difference at ground level between future and present scenario in the urban area of Turin, simulating residential emissions as areas sources. The average is calculated over the six coldest months of the year (October to March)

in 2014 was  $70 \mu\text{g}/\text{m}^3$  for NO<sub>x</sub> and  $63 \mu\text{g}/\text{m}^3$  for TSP. This means that the interventions considered would bring to a maximum NO<sub>x</sub> reduction of 5.7% and a maximum TSP reduction of 0.1% of the total concentration (considering base case). These numbers demonstrate a significant result for NO<sub>x</sub>, while the reduction of TSP is almost negligible.

Of the aforementioned studies, in Genon et al. (2009), two cases with 22 and 105 heating systems were considered and replaced with CHP and DH systems. In the first case, the average NO<sub>x</sub> concentration in the calculation domain declined by  $0.2 \mu\text{g}/\text{m}^3$ ; in the second case, an average improvement of  $1.7 \mu\text{g}/\text{m}^3$  was reported. A second study (Torchio et al. 2009) connected to the previous one indicated a reduction of PM concentration, with peaks reaching  $0.6 \mu\text{g}/\text{m}^3$ .

The results of additional simulations confirm that uncertainty is inevitably high, given the size of the system and the large number of factors involved. These results also show that a precise characterization of the emission scenario (height of the sources and reproduction of the building profiles in their surrounding) has a significant importance. A possible future scope for this study might therefore be a more detailed reconstruction of the residential areas and their sources.

The simulation of separate contributions, reported in Appendix A, confirms that the centralization of energy production brings some of the following advantages:

- A primary energy saving thanks to the improved efficiency of the system, as also reported by Finney et al. (2012).
- More control and reduction of the emissions: the modern CC plants (like TO-N) are equipped with advanced abatement systems and CEMS supervised by both the operator and the public environmental control agencies (Rezaie and Rosen 2012).

It is noteworthy that the exercise of these types of large-scale plants is also related to economic issues (Åberg et al. 2012; Jarre et al. 2016) that are not considered in this study, but can influence the configuration of the energy production (mainly in terms of electrical/thermal energy balance) and consequently the emissions scenario.

Implementing a largely consolidated model as CALPUFF resulted suitable to the magnitudes and scale of the study. The result of the environmental balance using area type sources provided a more uniform concentration compared to the use of barycentric stacks, that is what it could be expected in the reality. On the other hand, the disadvantage in using area type sources with CALPUFF is that the simulation of building downwash phenomena is not implemented.

Finally, the analysis of maximum and minimum values reveals a high variability of the average results due to the atmospheric conditions that may occur on the area of study. Turin is a scarcely ventilated city. The average value of wind speed measurements on a reference monitoring station located in Corso Principe Eugenio, Turin, from 1990 to 2004, was calculated equal to 0.9 m/s. The average annual number of wind calm days was equal to 75 (Arpa Piemonte 2007). This monitoring station is in a public garden, on flat terrain, at an altitude of 240 m above sea level. The instruments are placed at a height of 10 m. The closest obstacles (buildings) are at around 100 m. For wind speed calculation, data below the minimum wind speed threshold of the sensor were treated as absence of wind. Wind calm days were defined considering average wind speed together with the Beaufort scale classification. A wind calm day was defined as a day with average wind speed below 1.0 m/s and a maximum gust below 3.4 m/s.

The aforementioned factors foster situations of poor mixing and the formation of a stable urban boundary layer (Hanna et al. 1982). To obtain more information on the

variables leading to peak concentrations, weather records in correspondence of maximum and minimum values were investigated. The coexistence of the following factors was observed:

- Limited height of the mixed layer (below 100 m)
- Positive values of the Monin-Obukhov length
- Low horizontal wind speed (below 2 m/s)
- Low air temperature (between  $-2$  and  $3$  °C)
- Low total radiation (below  $60$  W/m<sup>2</sup>)

## Conclusion

This study reports the results of a survey on the local environmental effects of the potential extension of the DH network in the urban area of Turin. The results show that connecting part of the residential heating systems to the network produces an improvement to air quality in terms of NO<sub>x</sub> concentration at ground level. The reduction of contaminants is highest around the area subject to the intervention (northern and eastern districts of Turin), with positive effects also extending towards the city center. The average value of pollutant removal is estimated to be around  $1$  µg/m<sup>3</sup>, with a maximum between  $2$  and  $6$  µg/m<sup>3</sup>. The last Emission Inventory published by the Piedmont Region in 2010 shows that road traffic represents the main source of NO<sub>x</sub> and PM emissions, contributing to around 50% of total emissions. Industrial energy production and residential heating sectors account for around 7 and 5%, respectively. Considering these data, together with the analysis of annual emission flows reported in Table 5, the intervention object of the present study is not expected to bring a significant change in total emission of pollutants. On the other hand, if average concentrations are considered, a maximum 5.7% reduction for NO<sub>x</sub> may be obtained. This value would undoubtedly correspond to an environmental improvement at the local level in this heavily populated area subject to significant air quality issues.

Further considerations can then be made on the removal of obsolete boilers and the centralization of energy management. First, it is known that a centralized integrated system for energy production results in higher conversion efficiency, i.e., in a saving of primary energy. Secondly, large power units like TO-N are equipped with a continuous and precise monitoring system of air emissions that is controlled both by the operator and by the regional Environmental Protection Agency. These undoubtedly constitute positive aspects for urban pollution control and mitigation.

In conclusion, this study provides important information on the effects on air quality resulting from the modification of the energy management of an area or settlement.

From a more general point of view, the methodological approach used in this study included the combined analysis of the energy scenario associated with heat generation and distribution in DH networks, and the calculation of the potential dispersion of pollutants connected to it, with the aim of quantifying and locating the potential environmental impact. It is therefore a consistent and comprehensive methodology, suitable to be reproduced and developed for other energy management case studies or applications, laying a valid foundation for subsequent technical and economic in-depth analysis.

Consequently, the instrument that has been elaborated is very important from the scientific point of view; in fact, by using the proposed methodology, it is possible, on the basis of the elaboration of data measured on site (or obtained from the operators), to acquire relevant information to define the general environmental situation of the examined area.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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