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Abstract

The installation of district heating (DH) systems constitutes an advantage from the energetic, climate and air quality aspects. However, the configuration and operational features of a DH system affect significantly its environmental performance. The objective of the present study is the energetic and environmental assessment of DH networks that present differences in size and operating configurations, to define relevant environmental performance indicators. Three case studies in Italy are analysed, following a methodology based on the impact pathway approach that was presented by the authors in previous studies. Case studies are evaluated in terms of total emission, pollutant concentration (NO_x, CO, PM), and health damage external costs. Results show that lower pollutant emissions are associated with the installation of a DH system compared to autonomous residential boilers. Air quality is also improved and health externalities are reduced. The results of CO_2 savings are differentiated depending on the efficiency and emission factors of the systems. An inter-comparison of different cases is then presented, based on the elaboration of specific indicators of environmental and health impacts. This section shows that, besides the size of the DH system, other factors, such as population density and geographical distribution of pollutants concentration, are important. Among the indicators considered, those based on health externalities provide more complete and comparable information on the final impact of the alternative solutions on the exposed population. Their application seems thus promising for the evaluation of alternative planning strategies for DH systems.

Keywords: district heating network, air pollution, emission, environmental sustainability, health impact assessment, externalities.

Abbreviations

CHP combined heat and power

CO carbon monoxide

CO_{2eq} equivalent carbon dioxide

CRF concentration – response function

DH district heating

EF emission factor

GHG greenhouse gas

IPA impact pathway approach

MSW municipal solid waste

NO_x nitrous oxides

PBL planetary boundary layer

PM particulate matter

TSP total suspended particulate

WHO World Health Organization

1. Introduction

The improvement of air quality still represents a challenge in many urban areas around the world, including developed countries. Urban energy, climate, and air quality plans are increasingly integrating sustainability principles towards energy saving and pollution reduction, but much can still be done. Residential heating represents an important sector of emission of both GHG and macro-pollutants (NO_x, CO and particulate matter in particular). The European Environmental Agency reports that in the EU-28 in 2016, the commercial, institutional and households sector was responsible for the following emission share: 14% of NO_x, 55% of $PM_{2.5}$, 48% of CO, 4% of CH_4, and 11% of equivalent CO_2 (European Environmental Agency 2018).

In the framework of the European target for energy, climate, and air quality and energy policies, DH systems can contribute to increasing energy savings and reducing GHG and pollutant emissions. DH systems often show high conversion efficiencies, not only because of the possibility of integrating high-performance plants, but also thanks to the exploitability of renewable energy sources and waste heat (Guelpa et al., 2019). Current research activity is addressed to the technological development of low- temperature DH systems (30 - 70°C), i.e. the so-called 4th generation district heating, as reported by Lund et al. (2018). Research efforts are addressed to the integration of the various energy vectors, the increment of the efficiency of fossil-fuelled systems, the higher share of renewable energy sources. The interest in district cooling is also constantly increasing, due to the potential lower primary energy consumption than individual chiller systems installed in buildings (Sayegh et al. 2017). The integration of renewable energy sources is another important research area. The use of short-cycled wood biomass is promising in small community networks (Noussan et al., 2014). The integration of heat pumps (Bach et al., 2016), solar energy (Tian et al., 2019), and geothermal energy (Tester et al., 2016) is also studied and applied, although it is still facing important challenges. Combined Heat and Power (CHP) production presently provides about 56% of the heat demand of DH systems (Werner, 2017). If CHP is associated to a DH network, lower fuel energy is consumed compared to the separate production of heat and electricity (Mazhar et al. 2018; Lund et al. 2010). MSW-fuelled CHP schemes have been shown to reduce GHG emissions by up to 76% compared to conventional generation (Thorsen et al., 2018). In general, pollutant emission factors of DH systems are lower than those of autonomous installations, thanks to abatement measures which could not be techno-economically feasible at the scale of an individual boiler (Olsson et al. 2015; Ravina et al. 2018a). However, the configuration and operational features of a DH system significantly affect its environmental performance. The investigation of the environmental impacts of DH systems has been widely focusing on emissions, mostly on GHG. A limited number of studies is reported on macro-pollutants emissions, while few studies are found on the impacts of DH systems on air quality and human health. At today, decision-makers need efficient tools and comprehensive indicators to select the most sustainable technological solutions for DH systems. Such tools must consider the impacts of pollution sources on the final receptor, that, for urban areas, is represented by population. For these reasons, the evaluation must not stop only at considering emission balances. A deeper analysis of the impacts of planned interventions on air quality and human health must be included in the assessment. Previous studies by the authors have shown that methodologies that are based on the Impact Pathway Approach (IPA), by estimating air-pollutant induced health effects and external costs, can provide effective support in this sense (Ravina et al. 2019).

The objective of the present study is the energetic and environmental assessment of DH networks in different cases and operating configurations, to define relevant environmental performance indicators. For environmental indicator, it is intended one (or groups of) magnitudes or variables that can provide information on the environmental sustainability of DH networks. The concept of environmental sustainability, if applied to urban energy systems, means lowering the impacts on human health and ecosystem, both at the global and local scale. Indicators must thus provide relevant and concise information for stakeholders at the planning stage when the installation of a DH network is considered to i) replace existing heating systems (e.g. autonomous units) or ii) against (or in conjunction with) other potential alternative solutions (e.g. promotion of building refurbishment). Indicators can also, in principle, be employed at the time of evaluating the most suitable project configuration for a DH network (e.g. production technology, integration schemes, location of power plants, etc.). To overcome this objective, three case studies are reported and analyzed. The case studies relate to the DH networks of the Italian towns of Turin, Reggio Emilia, and Asti. In Turin and Reggio Emilia, the DH network is installed and operating, while in Asti it is still at the design stage. Single cases were firstly assessed separately following a methodology presented by the authors in previous works (Ravina et al. 2018b). The results were subsequently compared and elaborated to analyze relevant environmental indicators.

The paper is structured as follows. Section 2 presents the general methodology employed to evaluate the global and local impacts on human health and the environment of DH networks, compared with existing or alternative solutions. In this section, the case studies are described. Energy and emission balances are presented and compared with the alternative configuration. Section 3 presents the results of single cases. These results are presented in terms of comparative emission flows, pollutant concentration, and health externalities. A comparative elaboration and discussion is finally reported. Section 4 reports some conclusive remark.

2. Methodology

The methodology followed for the analysis of the environmental impacts of DH networks was presented in previous works by the authors. The first phase involved the calculation of gaseous flows emitted by the sources, starting from the definition of the energy balance of the entire system on an annual and hourly basis (Ravina et al. 2017). In this phase, local and global emissions were considered. Local emissions are represented by NO_x, CO and total suspended particulate (TSP). For global emissions, equivalent CO_2 ($CO2_{eq}$) was considered. In the second phase of the study, the impacts on air quality of the considered interventions were quantified in terms of concentration of pollutants, making use of dispersion modelling. Finally, a health impact assessment (HIA) was conducted, estimating the external costs linked to the change of concentration of nitrogen oxides and suspended particulate matter (Ravina et al. 2018b). The analysis of case studies was divided into the following operational steps:

- Definition of the system being studied;
- Collection of data concerning the physical and energy system under study;
- Definition of the energy balance of the system;
- Calculation of emission flow of pollutants and CO_2;
- Simulation of local dispersion of pollutants;
- Estimation of health externalities.

The cases presented in this study were selected because of their differences in terms of extension and configuration of the DH network, power conversion typology, and urban features (e.g. buildings, population density). All cases are located in the Po Valley, northern Italy. This area is characterized by low winds, in particular during summer and winter. The average value of wind speed in Turin, from 1990 to 2004, was 0.9 m/s. The average annual number of wind calm days was equal to 75 (Piedmont Regional Environmental Agency, 2007). During the cold season, pollutant dispersion is mainly regulated by local breeze regimens and soil heat-induced turbulence, which is minimum form December to February. Precipitations are minimum in January. Turin is the fourth largest city in Italy, with around 870,000 inhabitants and a population density of 6,730 inhabitants/km^2. Reggio Emilia is a district capital in the Emilia Romagna region (138,000 inhabitants, 740 inhabitants/km^2). Asti is a smaller district capital in Piedmont (75,500 inhabitants, 500 inhabitants/km^2). In all cases, 1-year period was studied. In the case of Turin and Reggio Emilia, the analysis was performed comparing the present situation with an alternative scenario. The present situation contemplates the actual environmental impacts of the DH system. The alternative scenario is represented by a total absence of the DH network, where centralized autonomous boilers are used for household heating. In the case of Asti, the emission scenario of centralized autonomous boilers was compared with the projected operational configuration of the DH network. The Asti case was simulated assuming the expected date of implementation of the installation, i.e. the year 2030. The application of the proposed methodology to both existing and planned networks, as well as differently sized networks, was adopted according to the objectives of the study. From one side, the assessment of present operating networks could provide information on i) sustainability of DH networks at the current state and ii) the effect of the network size on the environmental impacts. On another side, the analysis of a future case aimed at evaluating DH systems sustainability against the projected national and local policy scenarios, where energy consumption and emissions of the civil sector are expected to be significantly reduced.

2.1 Energy and emission balance

In the first stage of the study, the energy systems (DH networks and autonomous heating units) were characterized in terms of energy and emissions balance. Data of the energy conversion units powering the DH network were provided by the managing company of the DH network. These data are reported in Table 1.

Table 1. Information on the energy plants powering the DH networks considered in the study.

Town	Power plant	Description	Nominal power (th,el)	Stack height (m)	Stack diameter (m)
TURIN	TOC1	Combined cycle (gas turbine)	400 MW_e 220 MW_t	60	6
	TOB1	Integration and back-up boilers n°1-2-3	113 MW_t x 3	60	1.8
	TOC2	Combined cycle 1 (gas turbine)	395 MW_e 260 MW_t	60	7.0
		Combined cycle 2 (gas turbine)	383 MW_e 260 MW_t	60	7.0
	TOB2	Back-up boilers n°1-2-3	47 MW_t x 3	70	1.5

	TOB3	Integration and back-up boilers n°1-2-3	85 MW_t x 3	43	1.8
	TOB4	Integration and back-up boilers n°1-2-3	85 MW_t x 3	50	1.8
REGGIO EMILIA	REC1	Combined cycle (gas turbine)	41.6 MW_e 52 MW_t	40	3.3
	REC2	Cogenerating boilers	76.2 MW_t 18.6 MW_e	40	2.3
	REB1	Boilers n°1-2-3-4	68.5 MW_t	40	2
	REB2	Boilers n°1-2-3-4	64 MW_t	30	1.1
	REB3	Boilers n°1-2-3-4-5	24.6 MW_t	20	0.8
	REB4	Boilers n°1-2-3	42 MW_t	17	1.0
ASTI	ATC1	Cogenerating engines + backup boilers	2 x 10.3 MW_e 9.7 MW_t	35	1.0
	ATB1	Boilers n°1-2 + Solar thermal panels	2 x 20 MW_t 370 kW_t	35	1.1

These data were extracted from the continuous monitoring system of the plants. They included hourly rates of fuel consumption, net electricity production, net thermal energy delivered to the DH network, exhaust gas production (flow, temperature, and pressure), pollutants flow (NO_x and CO). The latest available (related to 2016) power units' emission flow rates were used. Data on periodic monitoring of exhaust gases (TSP concentration) were also provided by the company. These data were used to define the average TSP emission factor of the power plants. All the power plants considered in the case studies are fueled by natural gas.

Regarding the characterization of the undistributed energy system, the global efficiency of building heating installations does not depend only on the generation efficiency of boilers. It is also affected by distribution, regulation and emission systems. Each contribution also depends on building features, such as geometry and period of construction. For this reason, the thermal energy demand of buildings was calculated starting with the characterization of buildings in the study area. The model proposed by Fracastoro and Serraino (2011) was used for this purpose. This model was previously employed by local authorities for the definition of the energy plan of the Turin Metropolis (Turin Metropolis, 2015). It calculates average primary energy consumption (kWh/m^2 of floor area per year) of a building stock based on the methodology reported in the UNI/TS 11300-1:2008 regulation (Italian Organization for Standardization, 2008). Input data are geometric parameters of buildings (surface/volume ratio, S/V) and period of construction. Following this approach, the S/V ratio of the buildings currently replaced by the DH network was calculated by elaborating GIS-based data provided by regional geodatabases (Piedmont Region, n.d.; Emilia Romagna Region, n.d.). The period of construction was extracted by data of the 2011 Italian census (Italian National Institute of Statistics, 2011) and elaborated with the Quantum GIS software (Quantum GIS, 2020). The same methodology was used for the calculation of primary energy consumption in Reggio Emilia and Asti. In these cases, the model was adapted to these towns, based on the specific building features.

In the view of the comparative analysis, to not overestimate emissions, it was assumed that the totality of thermal units was fuelled by natural gas. Although other fuels are still employed, data of 2013 show that, in the selected urban areas, the share of natural gas was around 97% (Piedmont Region 2013). NO_x and TSP emission flow rates were calculated multiplying the hourly energy demand by the corresponding emission factor. NO_x and CO emission factors were set to 80 kg/GWh and 90 kg/GWh respectively, as established by

Piedmont Regional Decree n. 46–11968 (Piedmont Region 2009). The total PM emission factor was set to 4.3 kg/GWh according to the EMEP/EEA database (European Monitoring and Evaluation Programme and European Environmental Agency 2019). CO_2 emission factor was set to 198 kg/MWh, according to data from the Italian Institute for Environmental Protection and Research (2019). The annual electricity demand of residential buildings was calculated considering the available data reported on the municipal energy plans. It was assumed that the electricity was provided to the buildings through the Italian national transmission grid. Data on source composition and emission factors of the grid were extracted by the Italian Institute for Environmental Protection and Research (2019). For the Turin and Reggio Emilia cases, grid electricity was assumed to be produced by 37% of renewable sources and 63% of fossil fuels. An average conversion efficiency (kWh delivered per kWh primary energy) of 48.8% was considered for fossil fuel sources. The following emission factors were used for grid electricity: NO_x, 227.4 kg/GWh; CO, 97.7 kg/GWh; TSP, 5.4 kg/GWh; CO_2, 284.8 kg/MWh. An average share of network losses equal to 6.65% was considered. For the Asti case, the 2030 scenario reported in the Italian National Energy Strategy (Italian Ministry of Economic Development, Ministry of Environment, 2017) was assumed. According to this scenario, grid electricity was assumed to be produced by 60% of renewable sources and 40% of fossil fuels. A CO_2 emission factor of 208 kg/MWh was used. Emission factors of NO_x, CO and TSP were reduced proportionally to the increase of renewable sources share (from 37% to 60%, that is around 39%), corresponding to 138.7 kg/GWh, 59.6 kg/GWh and 3.3 kg/GWh respectively.

2.2 Pollutant dispersion modelling

Pollutant dispersion was simulated with the SPRAY model. SPRAY (Tinarelli et al. 1994; Tinarelli et al. 2000) is a three-dimensional Lagrangian particle dispersion model, which can take into account the spatial and temporal inhomogeneities of both mean flow and turbulence. Concentration fields generated by point, area or volume sources can be simulated by the model. The trajectory of the airborne pollutant is simulated through virtual particles: the mean motion is defined by the local wind and the dispersion is determined by solving the Langevin stochastic differential equations for the velocity fluctuations, reproducing the statistical characteristics of the turbulent flow. Therefore, different portions of the emitted plumes can suffer different atmospheric conditions, allowing realistic representations of complex phenomena, such as low wind-speed conditions, strong temperature inversions, flow over topography, land use, and terrain variability. SPRAY is a commercial model licensed by Arianet company (Arianet).

The meteorological input datasets were provided by Piemonte's Regional Environmental Agency for the Turin and Asti case studies, and by Emilia Romagna's Regional Environmental Agency for the Reggio Emilia case study. Three-dimensional wind fields were elaborated by running the SWIFT diagnostic mass-consistent model (Arianet; Aria Technologies). Wind fields were subsequently transferred to the SURFPRO3 model (Surface-atmosphere interface Processor) with other meteorological and geophysical input data. SURFPRO 3 allowed to estimate gridded fields of the planetary boundary layer (PBL) turbulence scaling parameters, horizontal and vertical eddy diffusivities, deposition velocities according to land cover type (e.g. roughness length) and atmospheric circulation conditions (wind speed, temperature, stability, solar radiation). SWIFT and SURFPRO3 outputs were finally transferred to the SPRAY model to calculate pollutant dispersion.

For the Turin case study, weather and orographic data covered a domain of 40×40 km^2 with a horizontal resolution of 500 m. For the Reggio Emilia and Asti case studies, the domain was of 20×20 km^2 with a horizontal resolution of 200 m. The modelling domains were the same as the input weather and orographic domains. The pollutants modelled were NO_x, CO, $PM_{2.5}$, and PM_{10}. Since these plants are fueled by natural gas, total particulate is expected to be composed mainly of fine and ultra-fine components (Chang et al. 2004). 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, 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 pollutants was conservatively used in the simulations. Power plants were simulated as point sources. The features of these sources are reported in Table 1. Residential boilers were simulated as area sources. Total emission flows of pollutants were distributed on the domain cells proportionally to the amount of primary energy consumed in each cell. To distribute the annual pollutant flow on an hourly basis, reference building heat demand rates were taken by the UNI EN 16147 regulation (Italian Organization for Standardization, 2017). The height of the emission sources was set to 25 m, according to the average conformation of buildings that is observed in these towns (5–8 floors). The diameter of the emission sources was set to 0.8 m, according to the standard sizing of centralized residential heating devices' chimneys. The exhaust gas exit temperature and velocity were set to 363 K and 5.0 m/s respectively.

For each of the simulated scenarios, the following concentration maps were generated: 1-hr and 24-hr mean concentration of NO_x, $PM_{2.5}$, PM_{10}, and CO; daily maximum 1-hour mean concentration of NO_x; maximum and minimum concentration of NO_x, $PM_{2.5}$, PM_{10}, and CO. Results were also reported in terms of concentration difference between the present and alternative energy configuration.

2.3 Health impact assessment

Health impact assessment of the DH networks was conducted through the estimate of health externalities applying the impact pathway approach (IPA) methodology. The DIATI Dispersion and Externalities Model (DIDEM), proposed by the authors in a previous study (Ravina et al. 2018b), was employed. The DIDEM model was designed to perform analyses of external health impacts and costs at the local scale (urban areas or similar). The main output provided by the model is the variation (reduction or increase) of external costs associated with the comparative analysis of alternative emission scenarios. For external costs, in this study, it is meant the marginal health damage costs, i.e. those costs generated by the effects on human health resulting from an extra unit of pollutant concentration. The DIDEM model allows connecting the simulation of pollutants dispersion with SPRAY model to the concentration-exposure-response functions (CRFs) provided by WHO recommendations (WHO 2013). The final economic module subsequently associates monetary values to the incremental incidence of disease calculated. The conceptual workflow of the DIDEM model is reported in Fig. **1**. The model also provides a preliminary estimate of the uncertainty through i) the implementation of different confidence levels on CRFs data, and ii) the application of confidence intervals in the definition of the slope of the CRFs. The implementation of different confidence levels is achieved by adopting the recommendations reported in the WHO's HRAPIE project (WHO 2013). In this project, the pollutant-outcome pairs were 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.

In the same report, confidence intervals in the calculation of the slope of the CRFs were also reported. The results of the health impact assessment were reported in terms of i) maps of distribution external costs per capita over the modelling domain, and ii) tables reporting the total variation of health effects and external costs associated to the considered scenarios. The reported results were differentiated depending on the level of confidence of the input health effect/response pairs considered. More information on DIDEM model can be found in Ravina et al. (2018b). A number of studies were recently presented involving the application of the DIDEM model to Turin's DH network. Comparative analyses were addressed to evaluate the future extension of Turin's DH network (Ravina et al. 2018c), alternative location of the power plants (Ravina et al. 2019), and the application of different pollutant dispersion models (Ravina et al. 2020a). Another recent work reported on the environmental and health impact assessment associated with the potential extensive diffusion of heat pumps for sanitary hot water production (Ravina et al. 2020b).

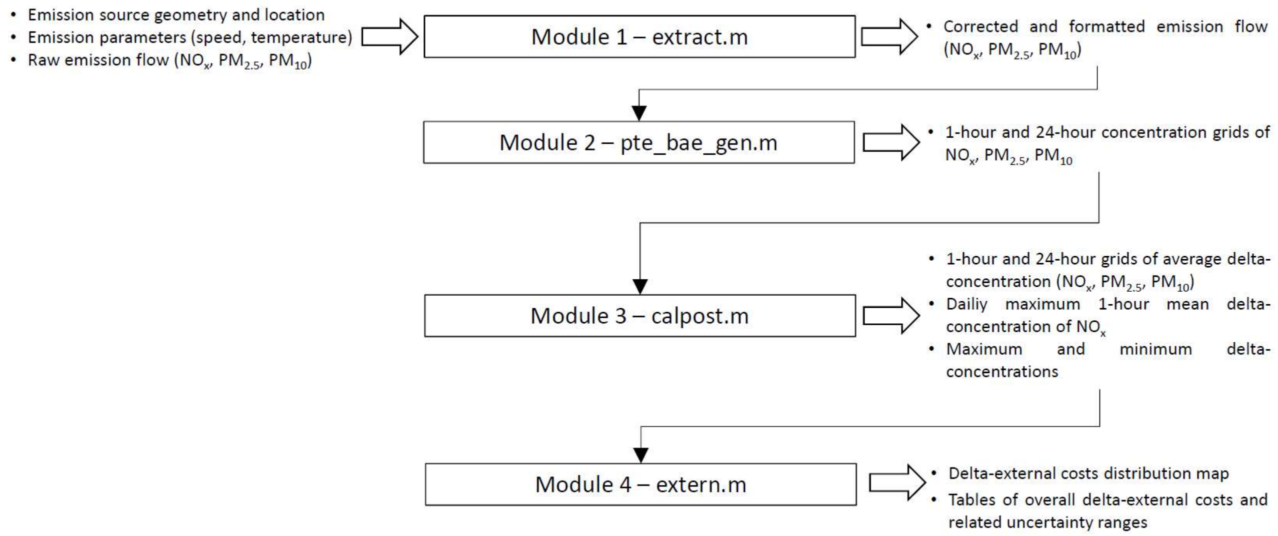


Fig. 1 Workflow of the DIDEM model

2.4 Case studies

The case studies are related to the DH networks of the Italian towns of Turin, Reggio Emilia, and Asti. In Turin and Reggio Emilia, the DH network is installed and operating, while in Asti it is still at the design stage. These cases present differences in terms of extension and configuration of the DH network, power conversion typology, and urban features (e.g. buildings, population density). The main features of each system are described in the following.

2.4.1 Turin

The project of Turin's DH network started in 1982 and progressively covered most of the urban area. The residential volume currently served amounts to about 68 million m^3. The length of the network amounts to around 530 km of pipelines and is one of the most extended in Europe. In the reference year of this study (2016), the residential volume connected amounted to 59,765,000 m^3, corresponding to 21,932,110 m^2 of floor area. Turin's DH network is currently powered by a system of two large combined cycle CHP plants fuelled by natural gas (here referred as TOC1 and TOC2). A set of four integration and reserve boilers completes the system. Information on Turin's DH network extension and configuration is reported in Fig. ***2***. For more information about the actual network structure and operating mode, refer to (Jarre et al. 2016). The TOC1 plant entered into operation in 2012. It is composed of a combined cycle unit having a total nominal power of 400 MW_e and 220 MW_{th}, and three backup boilers having 339 MW_{th} of total nominal power (here referred to as TOB1). The emission stack of the system is 60 m high. The TOC2 plant was initially built in 1954 and then subjected to several revamping interventions. It is composed of two combined cycle units having a total nominal power of 778 MW_e and 520 MW_{th}, and three backup boilers having 141 MW_{th} of total nominal power (here referred to as TOB2). The emission stack of the system is 70 m high. In 2014, during the last revamping, the plant was equipped with an advanced selective catalytic reduction system for the abatement of NO_x. In addition to the above-mentioned installations, two backup plants (here referred to as TOB3 and TOB4) are connected to the system. Each plant is composed of three boilers having a nominal thermal power of 85 MW_{th} each. The emission stack of the TOB3 plant is 43 m high. The emission stack of the TOB4 plant is 50 m high. Finally, four thermal storage units are present. In these units, heat is temporarily stored in large vessels in the form of pressurized steam. Such heat is delivered to the DH network to cover peaks of demand. A total storage volume of 16,000 m^3 is installed. In 2016, the share of thermal energy delivered to the DH network was the following: TOC2 system, 45%; TOC1 system, 39%; backup boilers, 6%. The remaining 10% was provided by the storage units. Total heat losses on the network were estimated to be around 16.3% of the produced thermal energy.

Building features of the residential units included in the area of actual extension of the DH network were analysed with the method described in section 2.1. The energy consumption model provided an average primary energy consumption of 180 kWh/m^2. Similar values can be found in McKenna et al. (2013) and the Tabula project (Institut Wohnen und Umwelt GmbH, 2016). This value was reduced to 169 kWh/m^2 to keep into account a 1.2% reduction rate of consumption per year, due to refurbishment interventions occurred in the period 2011-2016. For refurbishment interventions, it is meant insulation interventions on buildings, replacing heating installations with more efficient ones, and replacement of fossil fuels with renewable sources. The annual electricity demand of residential buildings was calculated considering a specific consumption of 27 kWh/m^2 of floor area, as reported in the local energy plan (Turin Metropolis 2015).

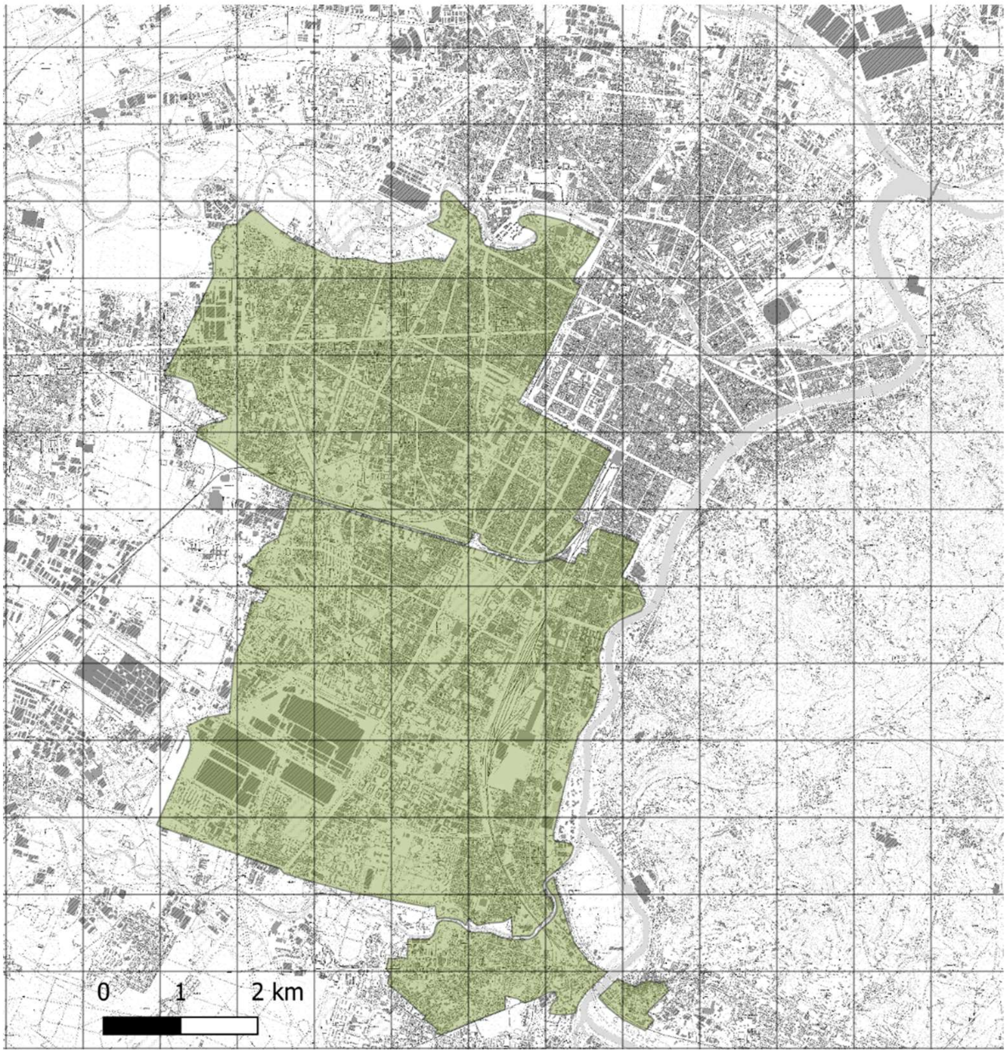


Fig. 2 Extension of the DH network in Turin

2.4.2 Reggio Emilia

Reggio Emilia has the fourth-largest DH network in Italy. The DH system in Reggio Emilia consists of a main network with superheated water at 120°C and other secondary networks at 90°C. Some areas of the city are also served by a district cooling network. The residential volume connected is around 13.3 million m^3, corresponding to 4,844,000 m^2 of floor area, and around 133,000 inhabitants served. The length of the network amounts to around 219 km of pipelines. The network is currently served by a cogeneration plant and four integration and backup plants. Four heat storage systems are also installed, with a total capacity of 1,600 m^3. The cogeneration plant is composed of a combined cycle unit (REC1) and two cogenerating heaters (REC2), having a total nominal power of 60.2 MW_e and 128.2 MW_{th}. The REB1 plant is composed of four backup boilers having 68.5 MW_{th} of total nominal power (in the same location of REC1 and REC2 plants). The emission stack of the system is 40 m high. The first of the three remaining backup and integration systems (here referred to as REB2) has a nominal thermal power of 64 MW_{th} and a stack height of 30 m. The second, here referred to as REB3, has a nominal thermal power of 24.7 MW_{th} and a stack height of 20 m. The third, here referred to as REB4, has a nominal thermal power of 42 MW_{th} and a stack height of 17 m. Information on Reggio Emilia's DH network extension and configuration is reported in Fig. ***3***. In 2016, the total amount of thermal energy delivered to the DH network was 400 GWh/y, of which 69% produced in cogeneration. Total heat losses on the network were estimated to be around 15.5% of the thermal energy produced.

The calculation of the thermal energy demand of buildings yielded an average primary energy demand of 172 kWh/m^2 of floor area. This value was reduced to 159 kWh/m^2 to keep into account a 1.2% reduction rate of consumption per year, due to refurbishment interventions occurred in the period 2011-2016. The annual electricity demand of residential buildings was calculated considering a specific consumption of 20 kWh/m^2 of floor area, as reported in the municipal energy plan (Reggio Emilia Municipality, 2011).

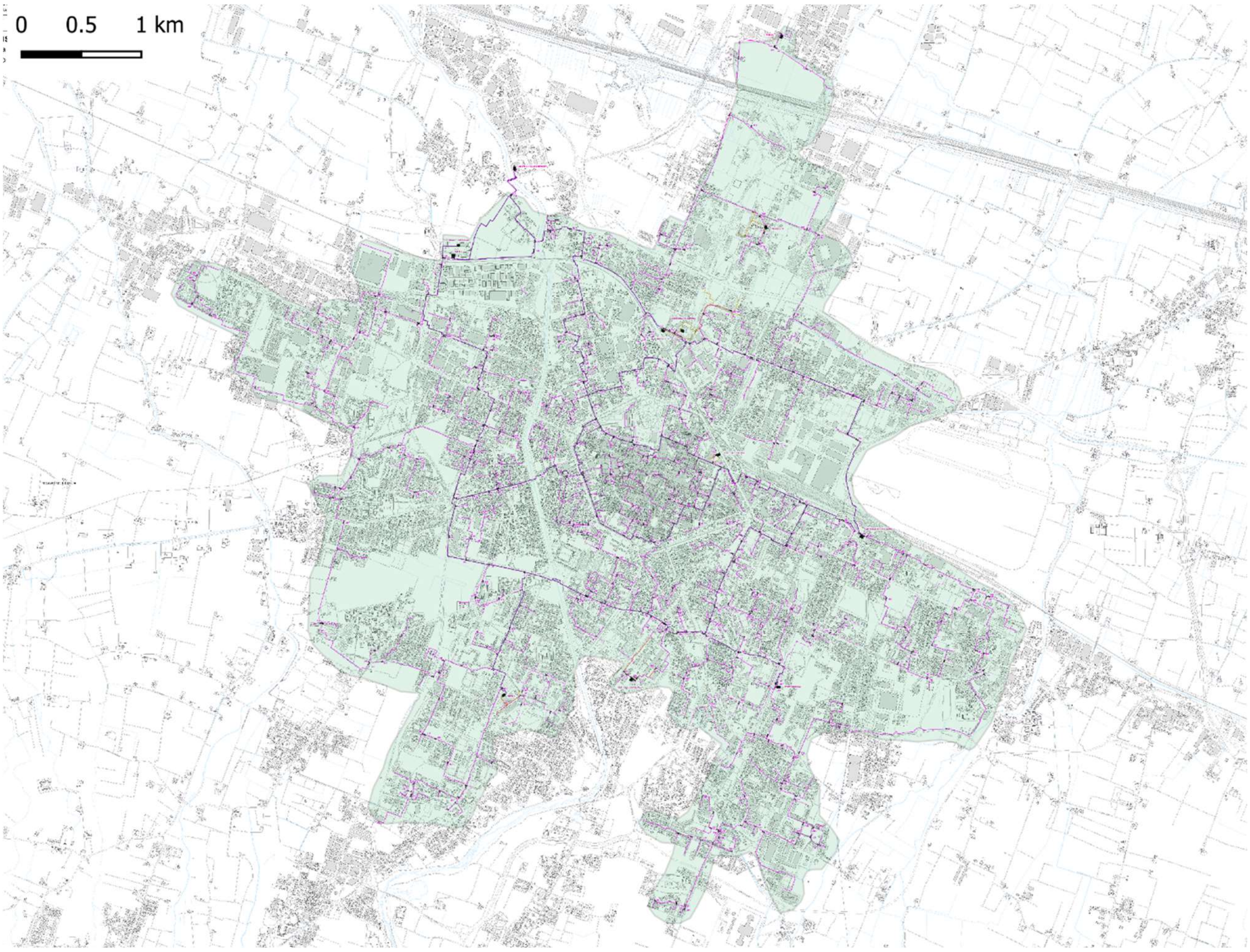


Fig. 3 Extension of the DH network in Reggio Emilia

2.4.3 Asti

Unlike previous cases reported in section 2.4.1 and 2.4.2, the DH network in the town is still at a planning stage. The study of the Asti DH network was thus referred to the year 2030. This year was chosen as a reference for two reasons. The first was that the DH system of Asti is expected to be completed and fully operating by 2030. The second was to provide a comparison against policy scenarios proposed by the regional Energy and Environmental Plan of Piedmont (Piedmont Region, 2018). In this plan, according to European and Italian guidelines (European Council, 2020), it is expected that a significant reduction of pollutant emission (around 20% against 2015) in the civil sector will be obtained by 2030. Such emission reduction will come from energy-saving interventions in buildings, renewal of heating installations, and replacement of fossil fuels with renewable sources, heat pumps in particular.

In this case study, data of the preliminary project were employed. These data were provided by the company that manages the system's construction and operation. The planning of Asti's DH network started from a screening of the potential areas of the town and building features. The screening phase revealed a total of around 650 buildings potentially interested in the connection to the DH network, corresponding to around 25,000 inhabitants, a residential volume of about 3.48 million m^3, and a floor area of 1,163,000 m^2. Based on these data, the operating company elaborated a preliminary design of the heat distribution grid. The expected size and location of the power units were also defined. Given the smaller size of this DH network, it was defined that the system will be powered by two cogeneration engines (here referred to as ATC1). ATC1 engines will provide a thermal power of 19.4 MW_{th} and electrical power of 20.6 MW_e. A backup and integration boiler will be installed in the same location, with a total thermal capacity of 20 MW_{th}. The emission stack of the system will be 35 m high. An additional unit including two backup and integration boilers (here referred to as ATB1) will be also installed in the area, with a total thermal capacity of 40 MW_{th} and a stack height of 35 m. Information on Asti's DH network extension and configuration is reported in Fig. ***4***. It was calculated that, in stationary operating conditions, the total amount of thermal energy delivered to the DH network will be around 134 GWh/y, of which 40% produced in cogeneration. Total heat losses on the network were estimated to be around 16% of the thermal energy produced.

For the calculation of the thermal energy demand of buildings, the model described in section 2.1 was used for the period 2011-2016. The application of this model yielded a value of specific energy consumption of 175 kWh/m^2. This value was reduced to 165 kWh/m^2 to keep into account a 1.2% reduction rate of consumption per year thanks to refurbishment interventions in the period 2011-2016. Subsequently, for estimating the reduction of energy consumption in the period 2016-2030, data from the regional Energy and Environmental Plan of Piedmont were used. In this Plan, the expected reduction of energy consumption in residential buildings for heating purposes, in the period 2016-2030, is 19.9%. The value of 165 kWh/m^2 was thus further reduced by 19.9%, obtaining 132 kWh/m^2. This latter value was considered to be the representative specific energy consumption of buildings in 2030. In the absence of a municipal energy plan, the annual electricity demand of residential buildings was calculated considering a specific consumption of 27 kWh/m^2 of floor area, equal to that of Turin.

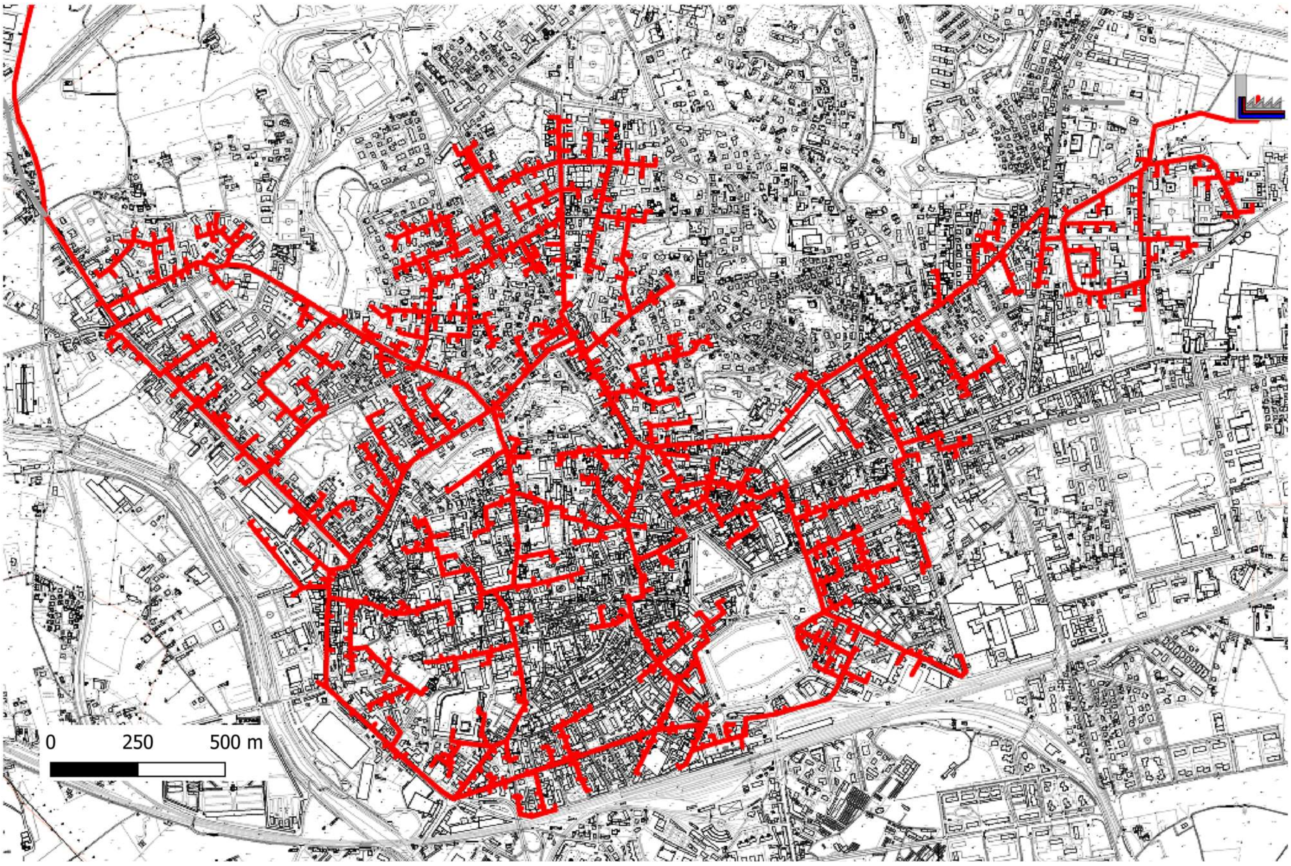


Fig. 4 Extension of the DH network in Asti

3. Results

The results of the elaboration of the three case studies are reported in the following. For each case study, the alternative operating configurations were analysed in terms of energy and emission balance, concentration of pollutants at ground level, and health externalities. A comparison of the results of single cases is finally reported.

3.1 Energy and emission balance

The energy balance of the three case studies is reported in Figures 5 to 7. In each figure, the energy consumption for thermal energy and electricity production was calculated. The operating configuration considering the presence of a DH network was compared with a scenario where the DH network was not present, based on the same amount of net energy provided to the final users. Total primary energy consumption, CO_2 emissions, and pollutants emissions of the system are reported in Table 2. Primary energy saving is between 7% (Asti) and 25% (Reggio Emilia). CO_2 emissions are reduced of 4.6% and 23% in the case of Turin and Reggio Emilia respectively, while a 1% increase is found in the case of Asti. The reduction of NO_x emission is between 54% (Asti) and 76% (Turin). The reduction of CO emission is between 46% (Asti) and 90% (Reggio Emilia). The reduction of TSP emission is between 44% (Asti) and 87% (Reggio Emilia).

3.2 Pollutants concentration

The comparison of operating scenarios in terms of pollutant concentration is reported in Figures 8 to 10. The concentration at ground level generated by the energy plants powering the DH network (case of DH installed) and by the residential boilers (case of DH not installed) is reported in onset a and b of these figures respectively. The concentration difference between the presence and absence of a DH network is reported in onset c. Finally, the delta external health costs per inhabitant are reported in onset d. These figures show that, for every pollutant, the concentration at ground level is significantly higher in the case of residential installations (no DH network). Average NO_x concentration reduction in the urban area is between around 1 $\mu g/m^3$ (Asti) and 3 $\mu g/m^3$ (Turin and Reggio Emilia). Average CO concentration reduction in the urban area is between around 1 $\mu g/m^3$ (Asti) and 4 $\mu g/m^3$ (Turin). Average $PM_{2.5}$ concentration reduction is around 0.1 $\mu g/m^3$ in Turin and Reggio Emilia, and 0.01 $\mu g/m^3$ in Asti. $PM_{2.5}$ concentration difference is not significant, due to the low emission factor of both power plants and residential boilers (all the simulated plants are fuelled by natural gas).

3.3 Health externalities

The estimates of the delta external health costs calculated by the DIDEM model show that, in general, the installation of a DH network corresponds to a marked reduction of health externalities. This reduction is 3 – 10 €/inhabitant/y for Turin, 3 – 4 €/inhabitant/y for Reggio Emilia, and 1 – 2 €/inhabitant/y for Asti. In this latter, an area is present where external costs are increased. However, this area is located outside the city center, and delta external costs do not exceed 0.5 €/inhabitant/y. If delta external costs are summed over the entire modelling domain and multiplied for the number of inhabitants, the total health externalities reduction reported in Table 3 is found. This table also reports the characterization of uncertainties associated to the method, that depend on i) the confidence level group on pollutant-outcome pairs (Group A and Group A+B), and ii) minimum, mean and maximum value of the relative risk (slope of the CRFs). The results show that total uncertainty is high. This is because the impact pathway methodology combines information from different sources such as pollutant exposure, population data, and CRFs. Each of these sources carries with it some degree of uncertainty, that affects the final cost estimate.

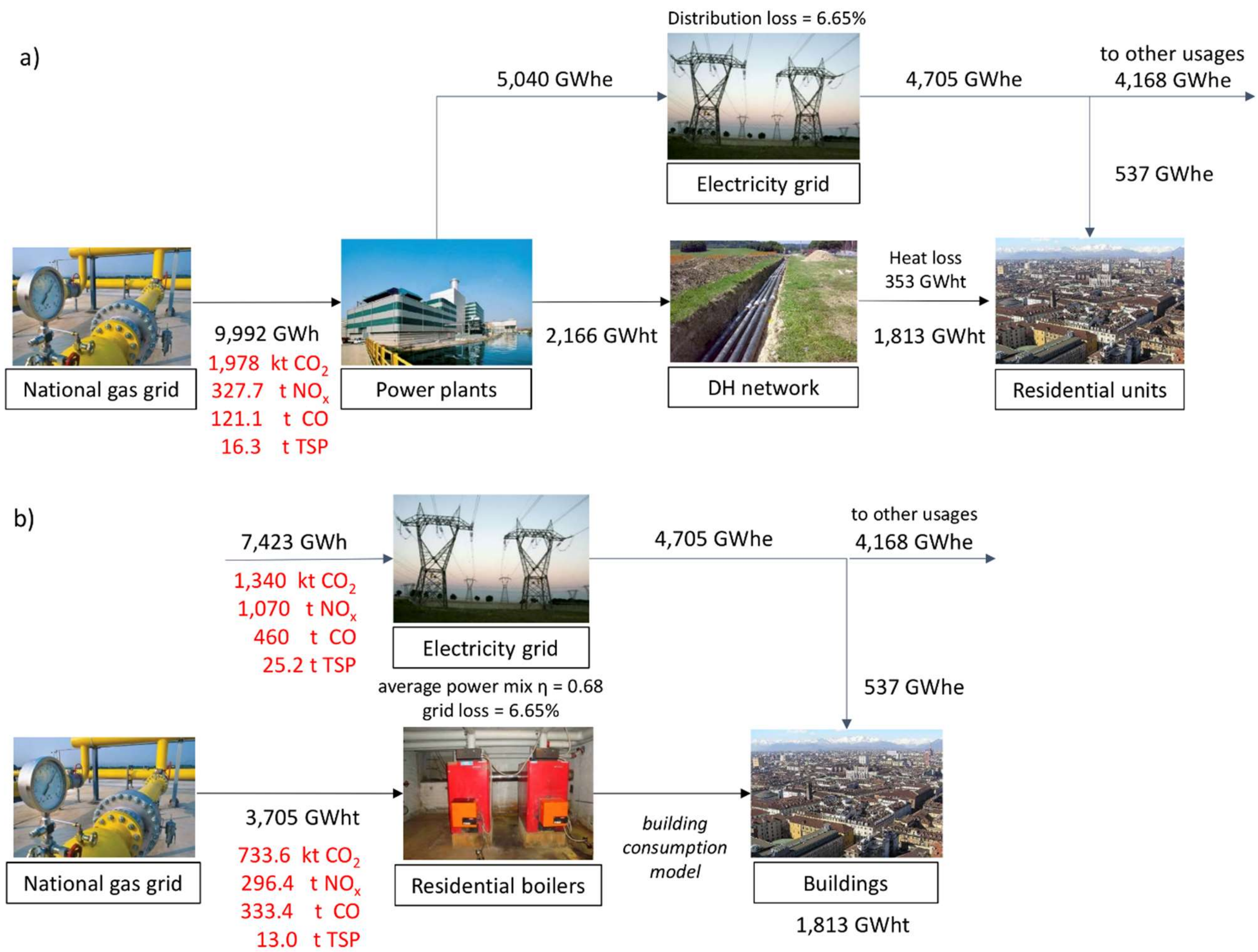
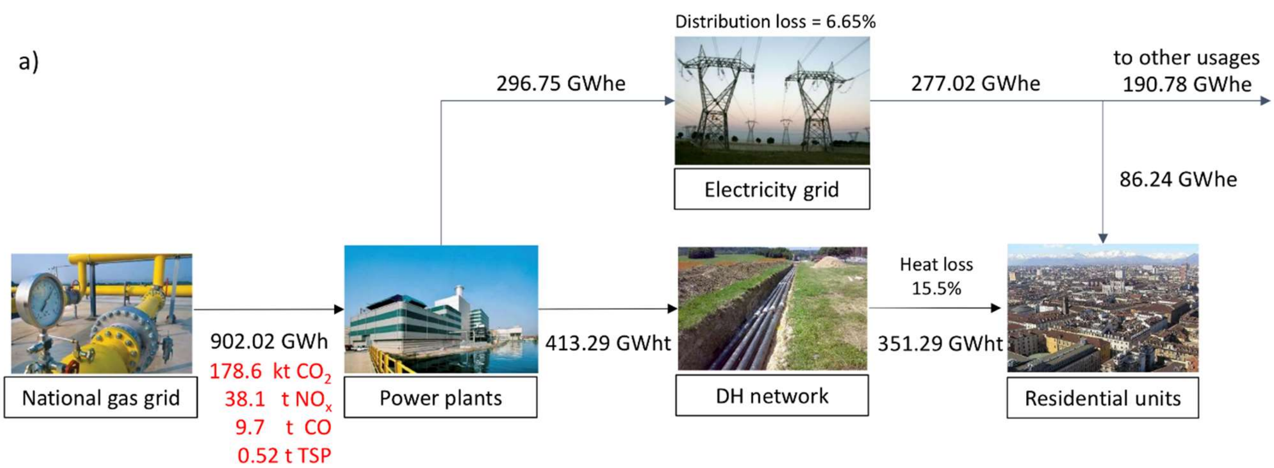


Fig. 5 Energy and emissions balance with (a) and without (b) DH network in Turin



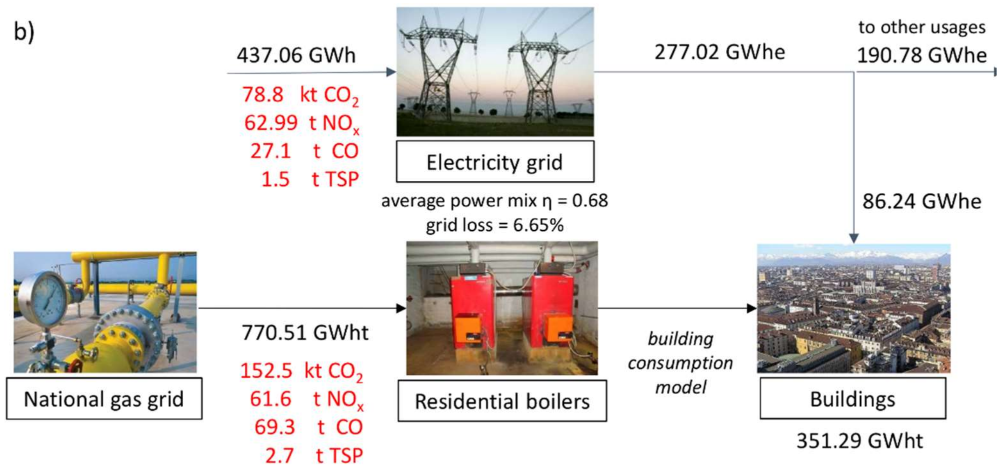


Fig. 6 Energy and emissions balance with (a) and without (b) DH network in Reggio Emilia

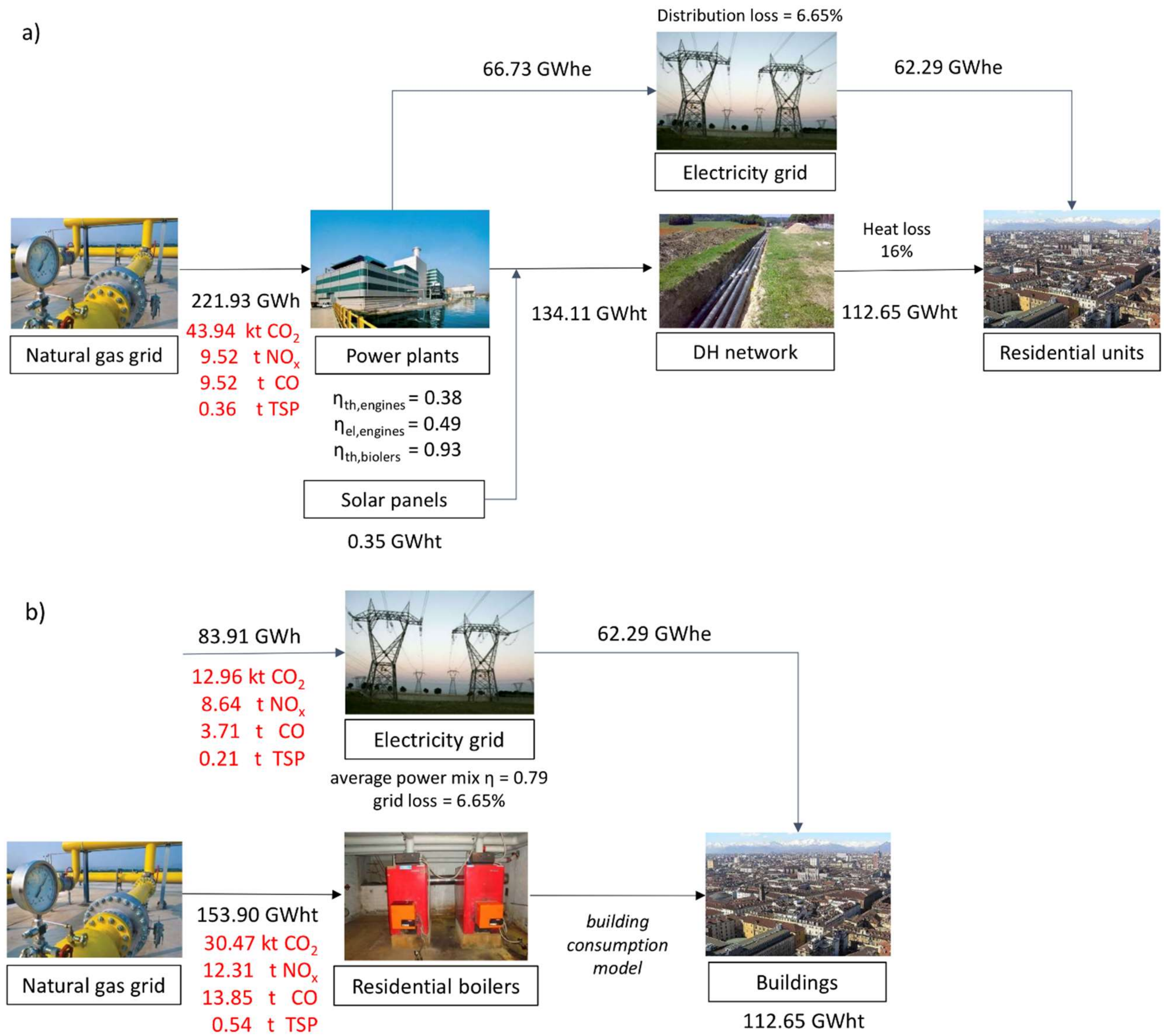
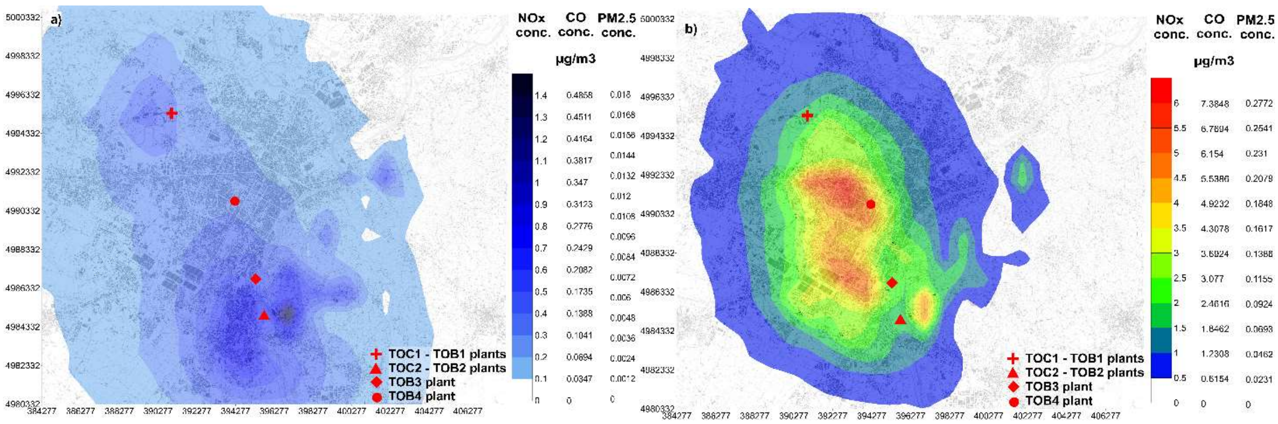


Fig. 7 Energy and emissions balance with (a) and without (b) DH network in Asti

Table 2. Calculation of energy and emissions savings connected to the presence of a DH network in the three towns considered in the study.

		Primary energy consumption (GWh/y)	CO_2 emission (kt/y)	NO_x emission (t/y)	CO emission (t/y)	TSP emission (t/y)
Turin	With DHN (electricity + heat)	9,992	1,978	327.7	121.1	16.3
	Without DHN (electricity + heat)	11,128 (7,423 + 3,705)	2,074 (1,340 + 734)	1,366.3 (1,069.9 + 296.4)	793.1 (459.7 + 333.4)	38.4 (25.4 + 13.0)
	Difference	- 1,136 (10.2%)	-96.0 (4.6%)	-1,038.6 (76%)	-672 (84%)	-22.1 (57%)
Reggio Emilia	With DHN (electricity + heat)	902.02	178.60	38.1	9.66	0.52
	Without DHN (electricity + heat)	1,207.61 (437.1 + 770.51)	231.46 (78.9 + 152.56)	124.63 (62.99 + 61.64)	96.41 (27.06 + 69.35)	4.19 (1.49 + 2.70)
	Difference	- 305.59 (25%)	- 52.86 (23%)	- 86.53 (69%)	- 86.95 (90%)	- 3.67 (87%)
Asti	With DHN (electricity + heat)	221.93	43.94	9,52	9,52	0,36
	Without DHN (electricity + heat)	237.81 (83.91 + 153.90)	43.43 (12.96 + 30.47)	20.95 (8.64 + 12.31)	17.56 (3.71 + 13.85)	0.64 (0.20 + 0.54)
	Difference	- 15.88 (7%)	0.5 (1%)	- 11.43 (54%)	- 8.04 (46%)	- 0.28 (44%)



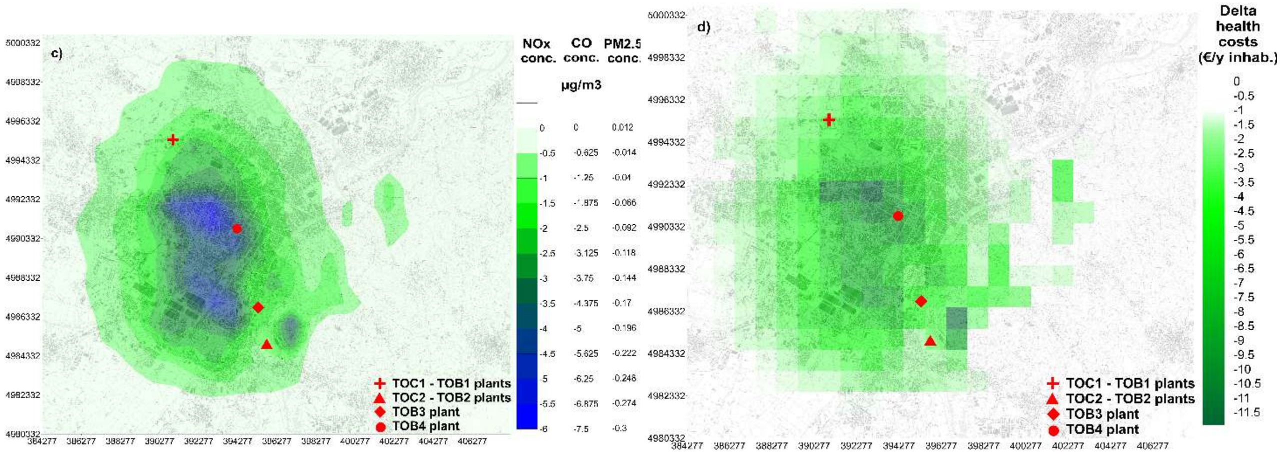


Fig. 8 Results of the application of CALPUFF and DIDEM models to the Turin case study, on an annual basis: a) 1-hour annual average concentration of NO_x, CO and $PM_{2.5}$ generated by the energy plants powering the DH network (scenario with a DH network); b) 1-hour annual average concentration of NO_x, CO and $PM_{2.5}$ generated by residential installations (scenario without a DH network); c) Average concentration difference between case a) and case b); d) Estimate of the delta external health costs per inhabitant calculated by the DIDEM model (difference between presence and absence of a DH network).

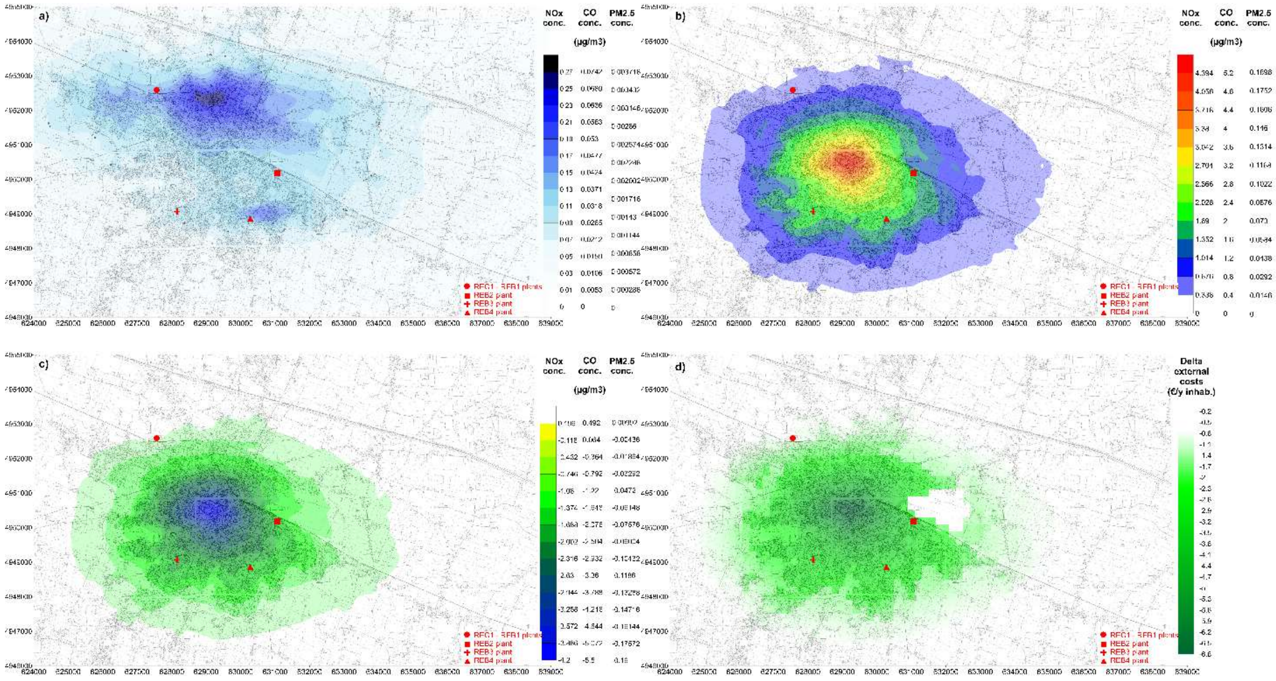


Fig. 9 Results of the application of CALPUFF and DIDEM models to the Reggio Emilia case study, on an annual basis: a) 1-hour annual average concentration of NO_x, CO and $PM_{2.5}$ generated by the energy plants powering the DH network (scenario with a DH network); b) 1-hour annual average concentration of NO_x, CO and $PM_{2.5}$ generated by residential installations (scenario without a DH network); c) Average concentration difference between case a) and case b); d) Estimate of the delta external health costs per inhabitant calculated by the DIDEM model (difference between presence and absence of a DH network).

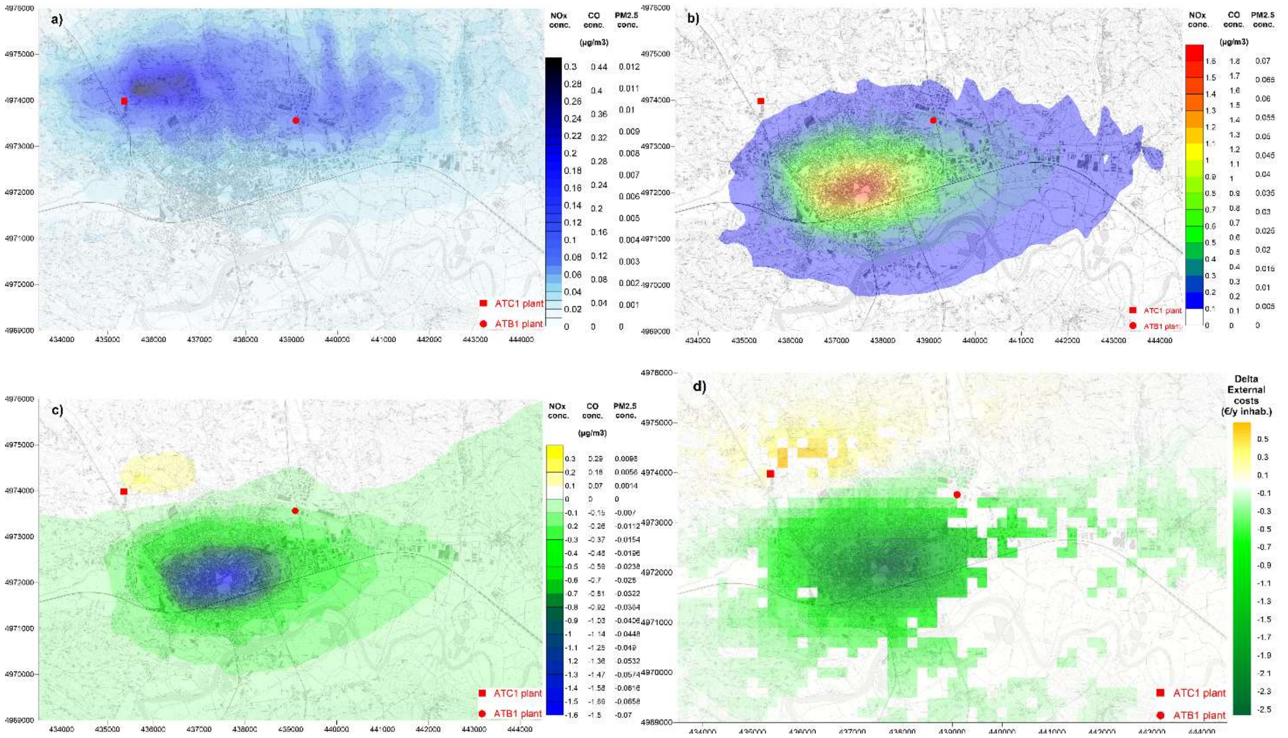


Fig. 10 Results of the application of CALPUFF and DIDEM models to the Asti case study, on an annual basis: a) 1-hour annual average concentration of NO_x, CO and $PM_{2.5}$ generated by the energy plants powering the DH network (scenario with a DH network); b) 1-hour annual average concentration of NO_x, CO and $PM_{2.5}$ generated by residential installations (scenario without a DH network); c) Average concentration difference between case a) and case b); d) Estimate of the delta external health costs per inhabitant calculated by the DIDEM model (difference between presence and absence of a DH network).

Table 3. Total delta external health costs (difference between presence and absence of a DH network) in the areas of study, calculated with the DIDEM model. Characterization of uncertainties depending on i) the confidence level group on pollutant-outcome pairs (Group A and Group A+B), and ii) Minimum, mean and maximum value of the relative risk (slope of the CRFs).

	Level of confidence on CRFs	**Delta external costs (minimum)**	**Delta external costs (mean)**	**Delta external costs (maximum)**
Turin	High (Group A)	2,625,000	6,040,000	8,720,000
	Medium (Group A + Group B)	18,540,000	39,330,000	58,150,000
Reggio Emilia	High (Group A)	47,000	103,000	148,000
	Medium (Group A + Group B)	304,000	546,000	806,000
Asti	High (Group A)	42,000	92,000	133,000
	Medium (Group A + Group B)	309,000	560,000	826,000

3.4 Comparison of the results

The case studies have a different extension of the DH network, configuration of the energy system, number of people and served buildings, and features of pollution sources. As these towns are all located in the Po valley, northern Italy, their meteorological and geophysical domain is similar. These towns are located on a flat, or slightly sloped terrain. Pollutants dispersion in the area is not affected by any particular geophysical element. The only exception is the case of Turin, where the hills located eastwards are a barrier for pollutant dispersion (Ravina et al. 2017).

Based on these considerations, the obtained results were elaborated to compare the studied cases. Emissions, concentrations, and externalities were compared with the relevant parameters of the analysed DH system, and several indicators were calculated. These are reported in Table 4. Residential volume served by the DH network, number of residents (municipality and modelling domain), and population density were selected as variables describing the system under study. The results reported in Table 4 are resumed in the following.

3.4.1 Average emission factors of the DH system (EF_{DH}).

The average emission factors of the DH system (EF_{DH}) were calculated as the sum of the pollutant emissions of all power plants divided by total primary energy consumption. The results show that EF_{DH} is related to the size of the system. EF_{DH} is, in general, higher for smaller systems and vice-versa. This is an expected result, since, in general, centralizing power production brings lower energy consumption and more efficient pollutant abatement systems (Calise et al. 2018). These values are also influenced by the amount of energy produced in cogeneration, which is higher in Turin than in Asti. EF_{DH} is, in general, lower than EF of residential boilers (cf. section 3.1). NO_x emission factor is between 32.7 kg/GWh and 42.9 kg/GWh. CO emission factor is between 10.7 kg/GWh and 42.9 kg/GWh. TSP emission factor is between 0.6 kg/GWh and 1.6 kg/GWh.

3.4.2 Specific emissions reduction (per capita or per residential volume) installing a DH network (ΔER_p and ΔER_v).

Emissions reduction per capita (ΔER_p) was calculated dividing the emissions reduction (Table 2) by the number of people living in the municipality. Emissions reduction per volume (ΔER_v) was calculated dividing the emissions reduction (Table 2) by the residential volume connected to the DH network. These two indicators provide slightly different information. The first shows the average emissions reduction in the entire municipality, thus it indicates the environmental benefit for all the residents. The values of ΔER_p are 0.15 – 1.19 kg/inhabitant (NO_x), 0.11 – 0.77 kg/inhabitant (CO) and 0.004 – 0.03 kg/inhabitant (TSP). For CO_2, this indicator is between a 0.38 t/inhabitant reduction (Reggio Emilia) and a 6.6E-03 t/inhabitant increase (Asti). The second indicator (ΔER_v) is related to the only areas served by the DH network. The values of ΔER_v are 3.3 – 21.9 g/m^3 (NO_x), 2.3 – 11.2 g/m^3 (CO) and 0.08 – 0.4 g/m^3 (TSP). For CO_2, this indicator is between a 3.98 kg/m^3 reduction (Reggio Emilia) and a 0.14 kg/m^3 increase (Asti). The results show that these indexes mostly depend on the efficiency of the proposed/replaced system, as well as on the assumptions made on emission factors. The size of the system is also affecting the results. The higher is the share of the DH network, the higher is the benefit for all the citizens. Similarly, the higher is the size of the network, the higher is the reduction of contaminant per unit of residential volume connected.

3.4.3 Average and maximum NO_x concentration reduction in the municipality (ΔC_{ave} and ΔC_{max}).

Average NO_x concentration reduction in the municipality was calculated elaborating the results of dispersion modelling with the software QGIS (Quantum GIS 2020) and MATLAB (Mathworks Inc. 2019). The only pollutant NO_x was considered, provided that the concentration distribution was the same for all pollutants. ΔC_{ave} is 1.65 μg/m^3 in Turin, 0.28 μg/m^3 in Reggio Emilia, and 0.06 μg/m^3 in Asti. This parameter indicates the general concentration reduction in the considered area. If compared to the average annual concentration measured by fixed monitoring stations, it provides a preliminary estimate of the contribution of the DH system to air quality improvement. Average NO_2 concentration measured by monitoring stations in 2015 was: 37 - 68 μg/m^3 in Turin, 40 μg/m^3 in Reggio Emilia, and 35 μg/m^3 in Asti (Piedmont Region Environmental Protection Agency; Emilia Romagna Region Environmental Protection Agency). Maximum NO_x concentration reduction (ΔC_{max}) is 5.63 μg/m^3 in Turin, 4.10 μg/m^3 in Reggio Emilia, and 1.53 μg/m^3 in Asti. The values show that, in some part of the town, higher concentration reduction are achieved. This depends on the position of the emission sources replaced by the DH network and, obviously, on the meteorological and geophysical conditions of the domain. The information gathered by analysing ΔC_{max} could be useful in view of the planning of a future network extension. Finally, these results show that the larger is the DH network, the higher is the ratio $\Delta C_{ave}/\Delta C_{max}$.

3.4.4 Specific concentration reduction (per capita or per residential volume) installing a DH network (ΔC_p and ΔC_v)

Concentration reduction per capita (ΔC_p) was calculated by dividing the emission reduction (ΔC_{ave}) by the number of people living in the municipality. Concentration reduction per volume (ΔC_v) was calculated dividing the emission reduction (ΔC_{ave}) by the residential volume connected to the DH network. Analogously to ΔER_p and ΔER_v, these indicators provide slightly different information. The values of ΔC_p are between 0.79 and 2.07 μg/m^3 per million inhabitants. ΔC_p of Reggio Emilia is higher than of ΔC_p of Turin, meaning that concentration reduction is more uniformly distributed over the area of the municipality. The values of ΔC_v are between 0.017 and 0.027 μg/m^3 per million m^3 of residential volume. ΔC_v shows a limited variability between the three cases. A possible explanation is that, under similar dispersion conditions, concentration reduction tends to be proportional to the size of the DH network.

3.4.5 Specific health externalities reduction (per capita or per residential volume) installing a DH network ($\Delta €_p$ and $\Delta €_v$).

Average health externalities reduction per capita ($\Delta €_p$) and per residential volume ($\Delta €_v$) were calculated starting by the output of DIDEM model (Table 3). The values of delta-costs in the domain cells contained in the municipality were extracted with the software QGIS and elaborated with MATLAB. Average and range of $\Delta €_p$ values are reported in Table 4. The difference among the cases is significant, and shifts from 0.25 €/inhabitant (Asti) to 8.25 €/inhabitant (Turin). From these results, it appears that the size of the system and population density affect significantly the externalities reduction. Average health externalities reduction per residential volume ($\Delta €_p$) was calculated dividing total externalities reduction (Table 3) by the residential volume connected to the DH network. $\Delta €_p$ is 0.043 – 0.972 €/m^3, 0.004 – 0.061 €/m^3, and 0.012 – 0.237 €/m^3 for Turin, Reggio Emilia, and Asti respectively. Surprisingly, $\Delta €_p$ value is greater in Asti than in Reggio Emilia. A possible explanation could be that, in Reggio Emilia, population exposure is lower in the areas where maximum concentration reduction occurs.

Table 4. Indicators of the environmental performance of the DH networks, on an annual basis.

Indicator (on an annual basis)	Unit	Turin	Reggio Emilia	Asti

Residential volume served by the DH network		m^3	59,765,000	13,273,000	3,480,000
Number of residents in the area (modelling domain)		-	2,205,000	209,000	104,000
Number of residents in the municipality		-	870,000	138,000	75,500
Average population density of the municipality		inhabitants/km^2	6,729	740	500
Average emission factor of the DH system (EF_{DH})	NO_x	kg/GWh	32.7	42.2	42.9
	CO		12.1	10.7	42.9
	TSP		1.6	0.6	1.6
Emission reduction per capita installing a DH network (ΔER_p)	CO_2	t/inhabitant	0.11	0.38	-6.6E-03
	NO_x	kg/inhabitant	1.19	0.63	0.15
	CO		0.77	0.63	0.11
	TSP		0.02	0.03	0.004
Emission reduction per residential volume installing a DH network (ΔER_v)	CO_2	kg/m^3	1.61	3.98	-0.14
	NO_x	g/m^3	21.9	6.5	3.3
	CO		11.2	6.5	2.3
	TSP		0.4	0.3	0.08
Average NO_x concentration reduction in the municipality (ΔC_{ave})		µg/m^3	1.65	0.28	0.06
Maximum NO_x concentration reduction (1-hr annual average) in the municipality (ΔC_{max})		µg/m^3	5.63	4.10	1.53
Average NO_x concentration reduction per capita installing a DH network (ΔC_p)		(µg/m^3/ 10^6 inhabitants)	1.90	2.07	0.79
Average NO_x concentration reduction per residential volume installing a DH network (ΔC_v)		(µg/m^3/ 10^6 m^3)	0.027	0.021	0.017
Average health externalities reduction per capita (Group A – Group A+B) ($\Delta €_p$)		€/inhabitant	8.75 (3.8 – 13.7)	1.45 (0.6 – 2.3)	0.25(0.1 – 0.4)
Average health externalities reduction per residential volume ($\Delta €_v$)		€/m^3	0.043 – 0.972	0.004 – 0.061	0.012 – 0.237

3.5 Discussion

The results reported in this study and the elaboration of environmental indicators bring important points of discussion. The results confirm that, in general, DH systems generate a lower emission of macro-pollutants than the conjunction of multiple autonomous heating units. This was demonstrated in numerous cases, for example in Göteborg (Sweden) or Milan (Italy), as reported within the framework of the District Energy in Cities Initiative (United Nations Environment Programme, 2020). Emission factors of DH systems are lower than those of small residential boilers thanks to more efficient pollutant abatement systems and better maintenance and monitoring of emissions. This is, in general, valid also for small district heating networks. A study on a small town in Croatia showed a potential 88% NO_x reduction associated with the installation of a DH network fuelled by natural gas. The average emission factor of the network was 36 kg/GWh. For TSP, the average emission factor was 0.3 kg/GWh (Doračić et al., 2018).

For GHG emission, the result reported in this study showed contrasting results. In the cases of Turin and Reggio Emilia, the emission reduction trend extensively reported in the bibliography (e.g., Rezaie and Rosen 2012; Andrić et al. 2017) was confirmed. The CO_2 emission factor of DH systems was in line with the average value reported by Noussan (2018), based on the study on 140 DH systems in Italy of different structure and size (0 - 0.30 kg/kWh). In the case of Asti, a slight increase of GHG emissions was found. This result is strongly affected by the precautionary assumptions made, both for building consumption (20% consumption reduction based on 2015) and electricity production in 2030 (60% share of renewable sources). Nevertheless, this result shows that, in the context of changing energy scenarios, future sustainability of DH systems will be increasingly depending on their design, size and operational structure.

Comparing the alternative energy systems in terms of concentrations, a general concentration reduction was found, in particular in the city center, and the areas served by the DH network. This is the result of replacing relatively low and central multiple pollution sources (20 – 30 m) with higher de-centralized point sources (40 – 70 m). Although dispersion modelling is a consolidated activity, few studies are reported in the bibliography concerning the comparative analysis of DH systems (Genon et al. 2009; van der Kamp and Bachmann 2015). The results reported in this study show that DH networks also bring significant advantages in terms of health impacts and costs reduction. This was reported in a previous study on the urban area of Turin (Ravina et al., 2018b). This study confirms that a reduction of externalities is also expected for DH networks of lower size, as in the cases of Reggio Emilia and Asti. The elaboration of the indicators reported in Table 4 tried to analyse the relevant factors affecting the environmental performance of DH networks. If results are compared in terms of specific emissions, it appears that the efficiency and emission factors of both the DH and the replaced system mainly affect the results. Comparing existing networks, two other factors show a major influence: the size of the network and the contribution of cogenerated energy to the system. Higher specific pollutant reduction (per capita o per residential volume connected) are associated to larger networks. Specific CO_2 reduction is more connected to the primary energy balance. Indicators based on specific concentrations introduce different considerations, as these only consider the air quality in the municipality and do not account for the electricity balance. In this case, the size of the network has still a major influence. Dispersion conditions, thus specific meteorology and geography of the area, also affect the results, as the higher value of ΔC_p in Reggio Emilia than Turin shows. Finally, if the comparison is done in terms of externalities reduction, results still depend mainly on the DH network size, but other factors appear, such as population density and geographical distribution of pollutants concentration. For these reasons, average health externalities reduction per capita ($\Delta €_p$) and per residential volume ($\Delta €_v$) seem to provide more complete information on the final impact of the alternative solutions on the final receptor (i.e. the resident population). In a previous study (Ravina et al. 2019), the authors analysed the application of models for the calculation of health damage externalities, highlighting that these tools can provide valuable support for the selection of the most environmentally and socially sustainable alternative of implementation. Given these considerations, the application of indicators based on health externalities for the evaluation of DH systems ($\Delta €_p$ and $\Delta €_v$) could be the object of future investigation.

4. Conclusion

This study reported a comprehensive evaluation of DH network emission in three Italian towns. Emissions of DH systems were compared to those of autonomous residential boilers, in terms of total annual flow, concentration distribution, and pollution-induced health externalities. The results confirmed that, in general, DH systems generate a lower NO_x, CO and TSP emissions than the conjunction of multiple autonomous heating units. However, especially for what concerning GHG emissions, this study also showed that efforts must be addressed to the optimization of the heat supply, as these DH networks have to be integrated with increasingly efficient residential systems and increasingly sustainable electricity systems. DH systems are currently facing the challenge of becoming thermal smart grids, with similar opportunities and risks of the better-known electric smart grids.

Considering urban air quality planning, DH systems represent an optimal solution. In this study, a novel comparative evaluation in terms of concentrations and health externalities was reported. The application of dispersion models is a consolidated activity in support of environmental impact assessment. Nevertheless, concentration maps must be interpreted, as they do not provide information on the final exposure risk of the population. The application of a model for the calculation of health impacts and costs represents an improvement in this perspective. In this study, the analysis of the DH network different in size and features were reported, and an inter-comparison between the DH systems of different towns was presented. Specific indicators were elaborated to analyse the relevant factors affecting the environmental performance of DH systems. The results showed that indicators based on health externalities seem to provide complete and comparable information in this sense. Their application should thus be further analysed in future extended investigations, considering different methodologies and more cases.

Conflict of interest

The authors declare no conflict of interest.

Ackowledgements

The authors kindly acknowledge IREN ENERGIA S.p.A., the Environmental Protection Agency of Piemonte Region (ARPA Piemonte) and the Environmental Protection Agency of Emilia Romagna Region (ARPAE) for the data provided.

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