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District heating networks: an inter-comparison of environmental indicators.

Marco Ravina^{1*}, Deborah Panepinto¹, Mariachiara Zanetti¹.

¹ Department of Environment, Land and Infrastructure Engineering, Corso Duca degli Abruzzi 24, 10129 Turin, Italy

*Corresponding author: Marco Ravina, Department of Environment, Land and Infrastructure Engineering, Corso Duca degli Abruzzi 24, 10129 Turin, Italy. Phone +39110907632. Fax: +39110907699. E-mail address: marco.ravina@polito.it

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 CO₂ 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

- 38 MSW municipal solid waste
- 39 NO_x nitrous oxides
- 40 PBL planetary boundary layer
- 41 PM particulate matter
- 42 TSP total suspended particulate
- 43 WHO World Health Organization

44 **1. Introduction**

45 The improvement of air quality still represents a challenge in many urban areas around the world, including
46 developed countries. Urban energy, climate, and air quality plans are increasingly integrating sustainability
47 principles towards energy saving and pollution reduction, but much can still be done. Residential heating
48 represents an important sector of emission of both GHG and macro-pollutants (NO_x, CO and particulate
49 matter in particular). The European Environmental Agency reports that in the EU-28 in 2016, the commercial,
50 institutional and households sector was responsible for the following emission share: 14% of NO_x, 55% of
51 PM_{2.5}, 48% of CO, 4% of CH₄, and 11% of equivalent CO₂ (European Environmental Agency 2018).

52 In the framework of the European target for energy, climate, and air quality and energy policies, DH systems
53 can contribute to increasing energy savings and reducing GHG and pollutant emissions. DH systems often
54 show high conversion efficiencies, not only because of the possibility of integrating high-performance plants,
55 but also thanks to the exploitability of renewable energy sources and waste heat (Guelpa et al., 2019).
56 Current research activity is addressed to the technological development of low- temperature DH systems (30
57 - 70°C), i.e. the so-called 4th generation district heating, as reported by Lund et al. (2018). Research efforts
58 are addressed to the integration of the various energy vectors, the increment of the efficiency of fossil-fuelled
59 systems, the higher share of renewable energy sources. The interest in district cooling is also constantly
60 increasing, due to the potential lower primary energy consumption than individual chiller systems installed
61 in buildings (Sayegh et al. 2017). The integration of renewable energy sources is another important research
62 area. The use of short-cycled wood biomass is promising in small community networks (Noussan et al., 2014).
63 The integration of heat pumps (Bach et al., 2016), solar energy (Tian et al., 2019), and geothermal energy
64 (Tester et al., 2016) is also studied and applied, although it is still facing important challenges. Combined Heat
65 and Power (CHP) production presently provides about 56% of the heat demand of DH systems (Werner,
66 2017). If CHP is associated to a DH network, lower fuel energy is consumed compared to the separate
67 production of heat and electricity (Mazhar et al. 2018; Lund et al. 2010). MSW-fuelled CHP schemes have
68 been shown to reduce GHG emissions by up to 76% compared to conventional generation (Thorsen et al.,
69 2018). In general, pollutant emission factors of DH systems are lower than those of autonomous installations,
70 thanks to abatement measures which could not be techno-economically feasible at the scale of an individual
71 boiler (Olsson et al. 2015; Ravina et al. 2018a). However, the configuration and operational features of a DH
72 system significantly affect its environmental performance. The investigation of the environmental impacts of
73 DH systems has been widely focusing on emissions, mostly on GHG. A limited number of studies is reported
74 on macro-pollutants emissions, while few studies are found on the impacts of DH systems on air quality and
75 human health. At today, decision-makers need efficient tools and comprehensive indicators to select the
76 most sustainable technological solutions for DH systems. Such tools must consider the impacts of pollution
77 sources on the final receptor, that, for urban areas, is represented by population. For these reasons, the
78 evaluation must not stop only at considering emission balances. A deeper analysis of the impacts of planned
79 interventions on air quality and human health must be included in the assessment. Previous studies by the
80 authors have shown that methodologies that are based on the Impact Pathway Approach (IPA), by estimating

81 air-pollutant induced health effects and external costs, can provide effective support in this sense (Ravina et
82 al. 2019).

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

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

106

107 **2. Methodology**

108

109 The methodology followed for the analysis of the environmental impacts of DH networks was presented in
110 previous works by the authors. The first phase involved the calculation of gaseous flows emitted by the
111 sources, starting from the definition of the energy balance of the entire system on an annual and hourly basis
112 (Ravina et al. 2017). In this phase, local and global emissions were considered. Local emissions are
113 represented by NO_x, CO and total suspended particulate (TSP). For global emissions, equivalent CO₂ (CO_{2eq})
114 was considered. In the second phase of the study, the impacts on air quality of the considered interventions
115 were quantified in terms of concentration of pollutants, making use of dispersion modelling. Finally, a health
116 impact assessment (HIA) was conducted, estimating the external costs linked to the change of concentration
117 of nitrogen oxides and suspended particulate matter (Ravina et al. 2018b). The analysis of case studies was
118 divided into the following operational steps:

- 119 • Definition of the system being studied;
- 120 • Collection of data concerning the physical and energy system under study;
- 121 • Definition of the energy balance of the system;
- 122 • Calculation of emission flow of pollutants and CO₂;
- 123 • Simulation of local dispersion of pollutants;
- 124 • Estimation of health externalities.

125 The cases presented in this study were selected because of their differences in terms of extension and
 126 configuration of the DH network, power conversion typology, and urban features (e.g. buildings, population
 127 density). All cases are located in the Po Valley, northern Italy. This area is characterized by low winds, in
 128 particular during summer and winter. The average value of wind speed in Turin, from 1990 to 2004, was 0.9
 129 m/s. The average annual number of wind calm days was equal to 75 (Piedmont Regional Environmental
 130 Agency, 2007). During the cold season, pollutant dispersion is mainly regulated by local breeze regimens and
 131 soil heat-induced turbulence, which is minimum from December to February. Precipitations are minimum in
 132 January. Turin is the fourth largest city in Italy, with around 870,000 inhabitants and a population density of
 133 6,730 inhabitants/km². Reggio Emilia is a district capital in the Emilia Romagna region (138,000 inhabitants,
 134 740 inhabitants/km²). Asti is a smaller district capital in Piedmont (75,500 inhabitants, 500 inhabitants/km²).
 135 In all cases, 1-year period was studied. In the case of Turin and Reggio Emilia, the analysis was performed
 136 comparing the present situation with an alternative scenario. The present situation contemplates the actual
 137 environmental impacts of the DH system. The alternative scenario is represented by a total absence of the
 138 DH network, where centralized autonomous boilers are used for household heating. In the case of Asti, the
 139 emission scenario of centralized autonomous boilers was compared with the projected operational
 140 configuration of the DH network. The Asti case was simulated assuming the expected date of implementation
 141 of the installation, i.e. the year 2030. The application of the proposed methodology to both existing and
 142 planned networks, as well as differently sized networks, was adopted according to the objectives of the study.
 143 From one side, the assessment of present operating networks could provide information on i) sustainability
 144 of DH networks at the current state and ii) the effect of the network size on the environmental impacts. On
 145 another side, the analysis of a future case aimed at evaluating DH systems sustainability against the projected
 146 national and local policy scenarios, where energy consumption and emissions of the civil sector are expected
 147 to be significantly reduced.

148 2.1 Energy and emission balance

149 In the first stage of the study, the energy systems (DH networks and autonomous heating units) were
 150 characterized in terms of energy and emissions balance. Data of the energy conversion units powering the
 151 DH network were provided by the managing company of the DH network. These data are reported in Table
 152 1.

153

154 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
	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
REGGIO EMILIA	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
	ATC1	Cogenerating engines + backup boilers	2 x 10.3 MW _e 9.7 MW _t	35	1.0
ASTI	ATB1	Boilers n°1-2 + Solar thermal panels	2 x 20 MW _t 370 kW _t	35	1.1

155

156 These data were extracted from the continuous monitoring system of the plants. They included hourly rates
 157 of fuel consumption, net electricity production, net thermal energy delivered to the DH network, exhaust gas
 158 production (flow, temperature, and pressure), pollutants flow (NO_x and CO). The latest available (related to
 159 2016) power units' emission flow rates were used. Data on periodic monitoring of exhaust gases (TSP
 160 concentration) were also provided by the company. These data were used to define the average TSP emission
 161 factor of the power plants. All the power plants considered in the case studies are fueled by natural gas.

162 Regarding the characterization of the undistributed energy system, the global efficiency of building heating
 163 installations does not depend only on the generation efficiency of boilers. It is also affected by distribution,
 164 regulation and emission systems. Each contribution also depends on building features, such as geometry and
 165 period of construction. For this reason, the thermal energy demand of buildings was calculated starting with
 166 the characterization of buildings in the study area. The model proposed by Fracastoro and Serraino (2011)
 167 was used for this purpose. This model was previously employed by local authorities for the definition of the
 168 energy plan of the Turin Metropolis (Turin Metropolis, 2015). It calculates average primary energy
 169 consumption (kWh/m² of floor area per year) of a building stock based on the methodology reported in the
 170 UNI/TS 11300-1:2008 regulation (Italian Organization for Standardization, 2008). Input data are geometric
 171 parameters of buildings (surface/volume ratio, S/V) and period of construction. Following this approach, the
 172 S/V ratio of the buildings currently replaced by the DH network was calculated by elaborating GIS-based data
 173 provided by regional geodatabases (Piedmont Region, n.d.; Emilia Romagna Region, n.d.). The period of
 174 construction was extracted by data of the 2011 Italian census (Italian National Institute of Statistics, 2011)
 175 and elaborated with the Quantum GIS software (Quantum GIS, 2020). The same methodology was used for
 176 the calculation of primary energy consumption in Reggio Emilia and Asti. In these cases, the model was
 177 adapted to these towns, based on the specific building features.

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

183 Piedmont Regional Decree n. 46–11968 (Piedmont Region 2009). The total PM emission factor was set to 4.3
184 kg/GWh according to the EMEP/EEA database (European Monitoring and Evaluation Programme and
185 European Environmental Agency 2019). CO₂ emission factor was set to 198 kg/MWh, according to data from
186 the Italian Institute for Environmental Protection and Research (2019). The annual electricity demand of
187 residential buildings was calculated considering the available data reported on the municipal energy plans. It
188 was assumed that the electricity was provided to the buildings through the Italian national transmission grid.
189 Data on source composition and emission factors of the grid were extracted by the Italian Institute for
190 Environmental Protection and Research (2019). For the Turin and Reggio Emilia cases, grid electricity was
191 assumed to be produced by 37% of renewable sources and 63% of fossil fuels. An average conversion
192 efficiency (kWh delivered per kWh primary energy) of 48.8% was considered for fossil fuel sources. The
193 following emission factors were used for grid electricity: NO_x, 227.4 kg/GWh; CO, 97.7 kg/GWh; TSP, 5.4
194 kg/GWh; CO₂, 284.8 kg/MWh. An average share of network losses equal to 6.65% was considered. For the
195 Asti case, the 2030 scenario reported in the Italian National Energy Strategy (Italian Ministry of Economic
196 Development, Ministry of Environment, 2017) was assumed. According to this scenario, grid electricity was
197 assumed to be produced by 60% of renewable sources and 40% of fossil fuels. A CO₂ emission factor of 208
198 kg/MWh was used. Emission factors of NO_x, CO and TSP were reduced proportionally to the increase of
199 renewable sources share (from 37% to 60%, that is around 39%), corresponding to 138.7 kg/GWh, 59.6
200 kg/GWh and 3.3 kg/GWh respectively.

201

202 2.2 Pollutant dispersion modelling

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

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

222 For the Turin case study, weather and orographic data covered a domain of 40 × 40 km² with a horizontal
223 resolution of 500 m. For the Reggio Emilia and Asti case studies, the domain was of 20 × 20 km² with a
224 horizontal resolution of 200 m. The modelling domains were the same as the input weather and orographic
225 domains. The pollutants modelled were NO_x, CO, PM_{2.5}, and PM₁₀. Since these plants are fueled by natural
226 gas, total particulate is expected to be composed mainly of fine and ultra-fine components (Chang et al.
227 2004). For this reason, PM_{2.5} and PM₁₀ emission flows were supposed equal to total PM emission flow. For
228 the combined-cycle cogeneration plants, jointly producing heat and electricity, it was not possible to allocate

229 the amount of NO_x and PM attributable to the only thermal energy transferred to the DH network. For this
230 reason, the total flow of pollutants was conservatively used in the simulations. Power plants were simulated
231 as point sources. The features of these sources are reported in Table 1. Residential boilers were simulated as
232 area sources. Total emission flows of pollutants were distributed on the domain cells proportionally to the
233 amount of primary energy consumed in each cell. To distribute the annual pollutant flow on an hourly basis,
234 reference building heat demand rates were taken by the UNI EN 16147 regulation (Italian Organization for
235 Standardization, 2017). The height of the emission sources was set to 25 m, according to the average
236 conformation of buildings that is observed in these towns (5–8 floors). The diameter of the emission sources
237 was set to 0.8 m, according to the standard sizing of centralized residential heating devices' chimneys. The
238 exhaust gas exit temperature and velocity were set to 363 K and 5.0 m/s respectively.

239 For each of the simulated scenarios, the following concentration maps were generated: 1-hr and 24-hr mean
240 concentration of NO_x, PM_{2.5}, PM₁₀, and CO; daily maximum 1-hour mean concentration of NO_x; maximum
241 and minimum concentration of NO_x, PM_{2.5}, PM₁₀, and CO. Results were also reported in terms of
242 concentration difference between the present and alternative energy configuration.

243

244 2.3 Health impact assessment

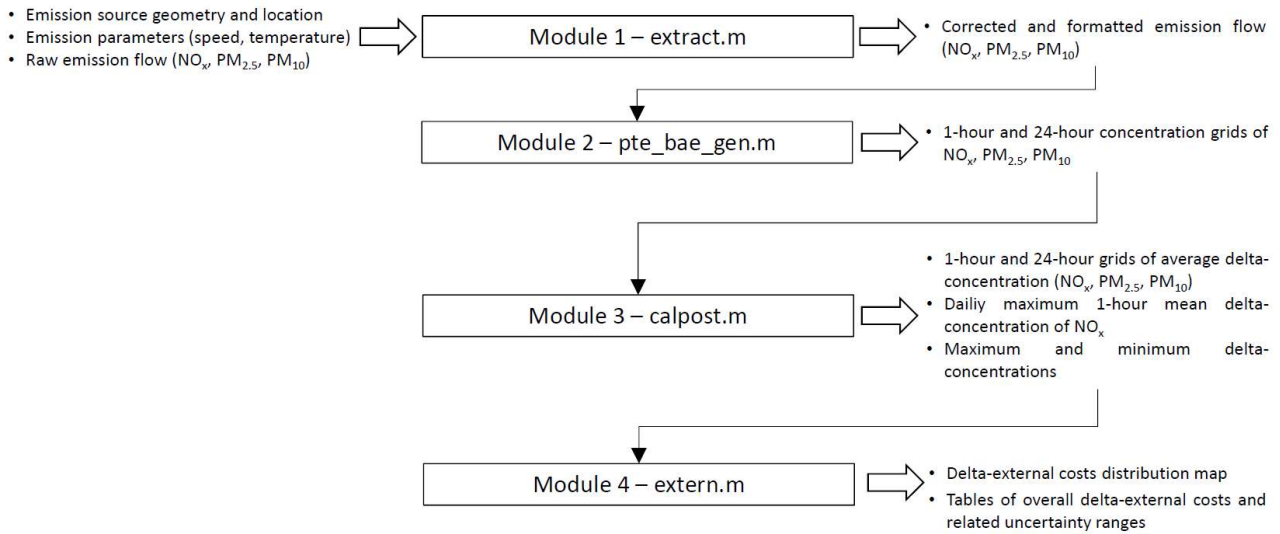
245 Health impact assessment of the DH networks was conducted through the estimate of health externalities
246 applying the impact pathway approach (IPA) methodology. The DIATI Dispersion and Externalities Model
247 (DIDEM), proposed by the authors in a previous study (Ravina et al. 2018b), was employed.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

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

265 In the same report, confidence intervals in the calculation of the slope of the CRFs were also reported. The
266 results of the health impact assessment were reported in terms of i) maps of distribution external costs per
267 capita over the modelling domain, and ii) tables reporting the total variation of health effects and external
268 costs associated to the considered scenarios. The reported results were differentiated depending on the level
269 of confidence of the input health effect/response pairs considered. More information on DIDEM model can
270 be found in Ravina et al. (2018b). A number of studies were recently presented involving the application of
271 the DIDEM model to Turin's DH network. Comparative analyses were addressed to evaluate the future
272 extension of Turin's DH network (Ravina et al. 2018c), alternative location of the power plants (Ravina et al.
273 2019), and the application of different pollutant dispersion models (Ravina et al. 2020a). Another recent work

274 reported on the environmental and health impact assessment associated with the potential extensive
 275 diffusion of heat pumps for sanitary hot water production (Ravina et al. 2020b).

276



277

278 **Fig. 1** Workflow of the DIDEM model

279

280 **2.4 Case studies**

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

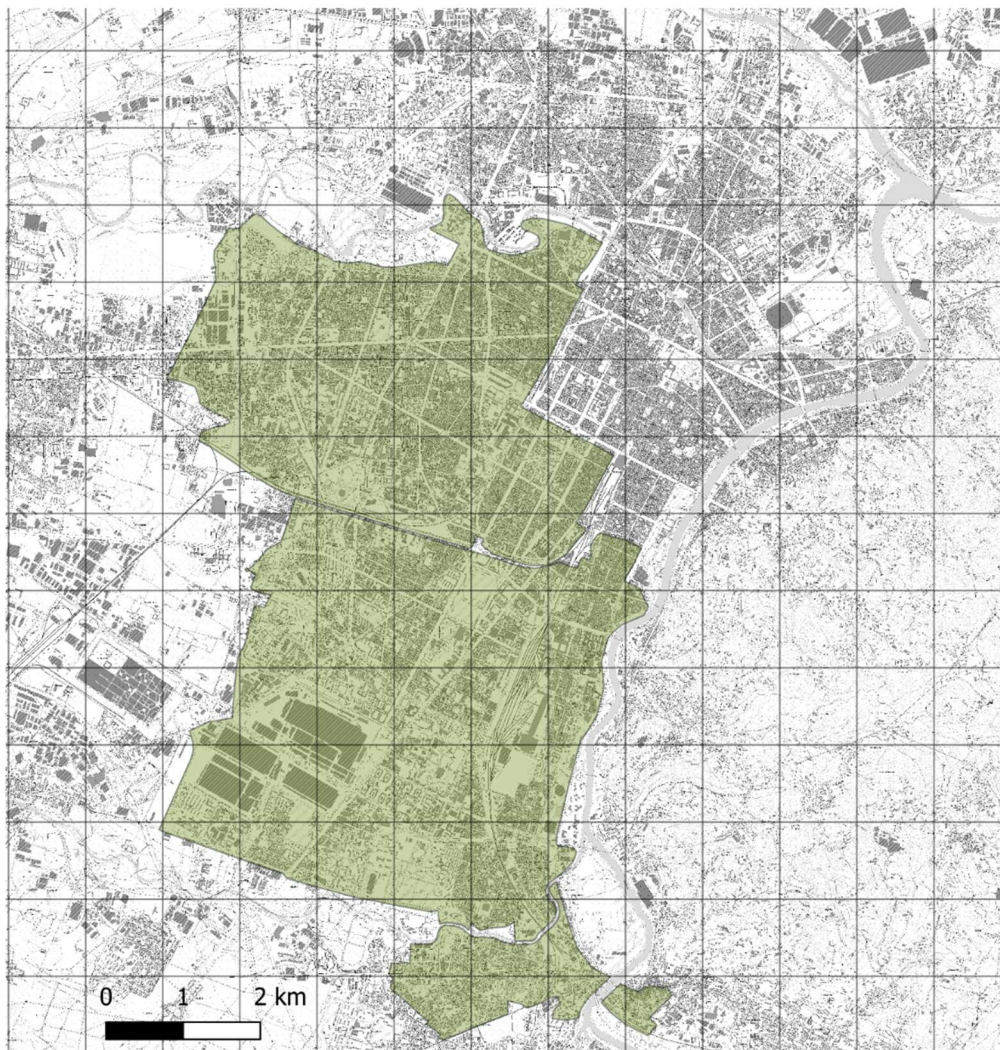
286 **2.4.1 Turin**

287 The project of Turin’s DH network started in 1982 and progressively covered most of the urban area. The
 288 residential volume currently served amounts to about 68 million m³. The length of the network amounts to
 289 around 530 km of pipelines and is one of the most extended in Europe. In the reference year of this study
 290 (2016), the residential volume connected amounted to 59,765,000 m³, corresponding to 21,932,110 m² of
 291 floor area. Turin’s DH network is currently powered by a system of two large combined cycle CHP plants
 292 fuelled by natural gas (here referred as TOC1 and TOC2). A set of four integration and reserve boilers
 293 completes the system. Information on Turin’s DH network extension and configuration is reported in Fig. 2.
 294 For more information about the actual network structure and operating mode, refer to (Jarre et al. 2016).
 295 The TOC1 plant entered into operation in 2012. It is composed of a combined cycle unit having a total nominal
 296 power of 400 MW_e and 220 MW_{th}, and three backup boilers having 339 MW_{th} of total nominal power (here
 297 referred to as TOB1). The emission stack of the system is 60 m high. The TOC2 plant was initially built in 1954
 298 and then subjected to several revamping interventions. It is composed of two combined cycle units having a
 299 total nominal power of 778 MW_e and 520 MW_{th}, and three backup boilers having 141 MW_{th} of total nominal
 300 power (here referred to as TOB2). The emission stack of the system is 70 m high. In 2014, during the last
 301 revamping, the plant was equipped with an advanced selective catalytic reduction system for the abatement
 302 of NO_x. In addition to the above-mentioned installations, two backup plants (here referred to as TOB3 and
 303 TOB4) are connected to the system. Each plant is composed of three boilers having a nominal thermal power
 304 of 85 MW_{th} each. The emission stack of the TOB3 plant is 43 m high. The emission stack of the TOB4 plant is
 305 50 m high. Finally, four thermal storage units are present. In these units, heat is temporarily stored in large

306 vessels in the form of pressurized steam. Such heat is delivered to the DH network to cover peaks of demand.
307 A total storage volume of 16,000 m³ is installed. In 2016, the share of thermal energy delivered to the DH
308 network was the following: TOC2 system, 45%; TOC1 system, 39%; backup boilers, 6%. The remaining 10%
309 was provided by the storage units. Total heat losses on the network were estimated to be around 16.3% of
310 the produced thermal energy.

311 Building features of the residential units included in the area of actual extension of the DH network were
312 analysed with the method described in section 2.1. The energy consumption model provided an average
313 primary energy consumption of 180 kWh/m². Similar values can be found in McKenna et al. (2013) and the
314 Tabula project (Institut Wohnen und Umwelt GmbH, 2016). This value was reduced to 169 kWh/m² to keep
315 into account a 1.2% reduction rate of consumption per year, due to refurbishment interventions occurred in
316 the period 2011-2016. For refurbishment interventions, it is meant insulation interventions on buildings,
317 replacing heating installations with more efficient ones, and replacement of fossil fuels with renewable
318 sources. The annual electricity demand of residential buildings was calculated considering a specific
319 consumption of 27 kWh/m² of floor area, as reported in the local energy plan (Turin Metropolis 2015).

320



321

322 **Fig. 2** Extension of the DH network in Turin

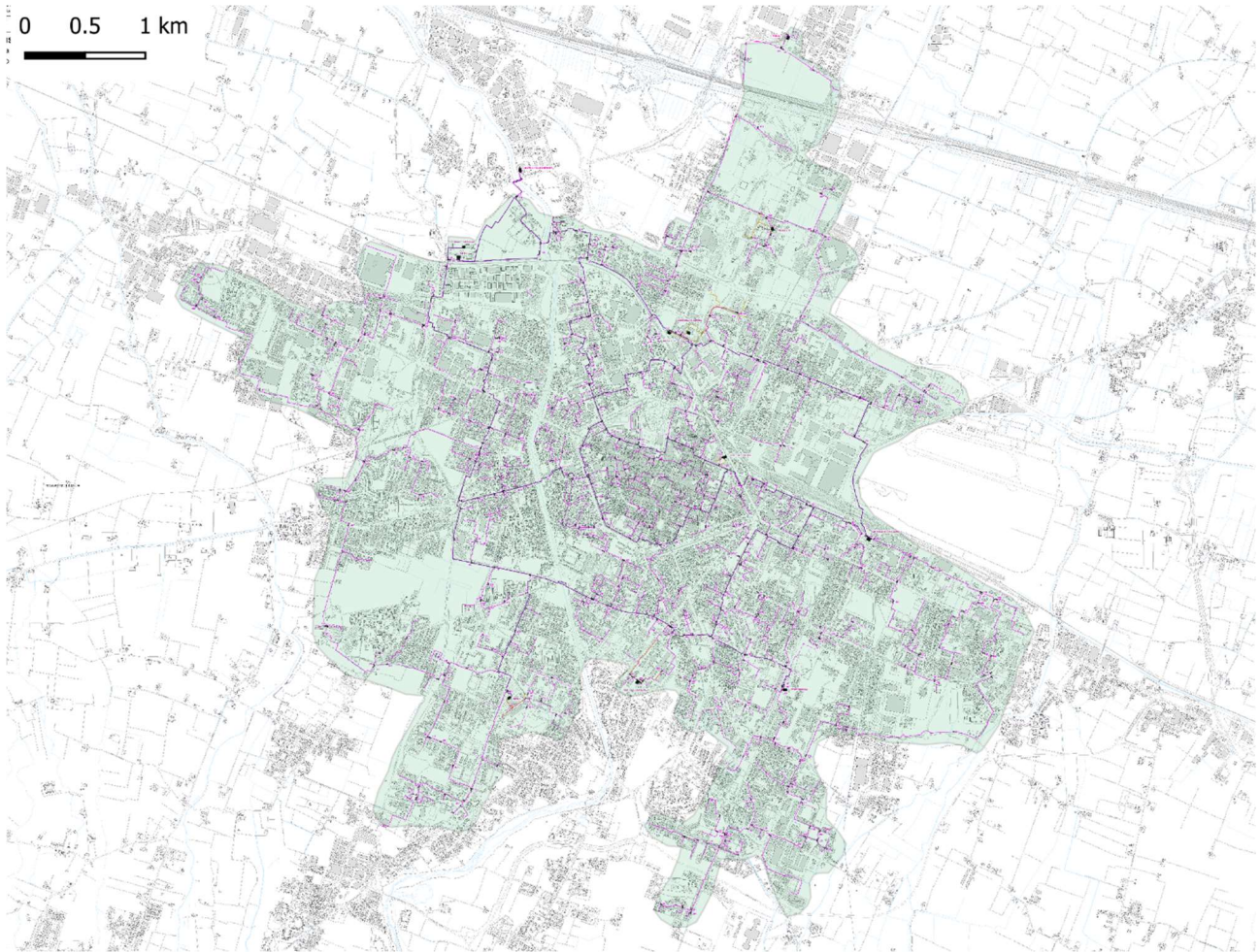
323

324 2.4.2 Reggio Emilia

325 Reggio Emilia has the fourth-largest DH network in Italy. The DH system in Reggio Emilia consists of a main
326 network with superheated water at 120°C and other secondary networks at 90°C. Some areas of the city are
327 also served by a district cooling network. The residential volume connected is around 13.3 million m³,
328 corresponding to 4,844,000 m² of floor area, and around 133,000 inhabitants served. The length of the
329 network amounts to around 219 km of pipelines. The network is currently served by a cogeneration plant
330 and four integration and backup plants. Four heat storage systems are also installed, with a total capacity of
331 1,600 m³. The cogeneration plant is composed of a combined cycle unit (REC1) and two cogenerating heaters
332 (REC2), having a total nominal power of 60.2 MW_e and 128.2 MW_{th}. The REB1 plant is composed of four
333 backup boilers having 68.5 MW_{th} of total nominal power (in the same location of REC1 and REC2 plants). The
334 emission stack of the system is 40 m high. The first of the three remaining backup and integration systems
335 (here referred to as REB2) has a nominal thermal power of 64 MW_{th} and a stack height of 30 m. The second,
336 here referred to as REB3, has a nominal thermal power of 24.7 MW_{th} and a stack height of 20 m. The third,
337 here referred to as REB4, has a nominal thermal power of 42 MW_{th} and a stack height of 17 m. Information
338 on Reggio Emilia's DH network extension and configuration is reported in Fig. 3. In 2016, the total amount of
339 thermal energy delivered to the DH network was 400 GWh/y, of which 69% produced in cogeneration. Total
340 heat losses on the network were estimated to be around 15.5% of the thermal energy produced.

341 The calculation of the thermal energy demand of buildings yielded an average primary energy demand of
342 172 kWh/m² of floor area. This value was reduced to 159 kWh/m² to keep into account a 1.2% reduction rate
343 of consumption per year, due to refurbishment interventions occurred in the period 2011-2016. The annual
344 electricity demand of residential buildings was calculated considering a specific consumption of 20 kWh/m²
345 of floor area, as reported in the municipal energy plan (Reggio Emilia Municipality, 2011).

346



347

348 **Fig. 3** Extension of the DH network in Reggio Emilia

349

350 2.4.3 Asti

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

360 In this case study, data of the preliminary project were employed. These data were provided by the company
 361 that manages the system's construction and operation. The planning of Asti's DH network started from a
 362 screening of the potential areas of the town and building features. The screening phase revealed a total of
 363 around 650 buildings potentially interested in the connection to the DH network, corresponding to around
 364 25,000 inhabitants, a residential volume of about 3.48 million m³, and a floor area of 1,163,000 m². Based on
 365 these data, the operating company elaborated a preliminary design of the heat distribution grid. The
 366 expected size and location of the power units were also defined. Given the smaller size of this DH network,
 367 it was defined that the system will be powered by two cogeneration engines (here referred to as ATC1). ATC1
 368 engines will provide a thermal power of 19.4 MW_{th} and electrical power of 20.6 MW_e. A backup and

369 integration boiler will be installed in the same location, with a total thermal capacity of 20 MW_{th}. The
370 emission stack of the system will be 35 m high. An additional unit including two backup and integration boilers
371 (here referred to as ATB1) will be also installed in the area, with a total thermal capacity of 40 MW_{th} and a
372 stack height of 35 m. Information on Asti's DH network extension and configuration is reported in Fig. 4. It
373 was calculated that, in stationary operating conditions, the total amount of thermal energy delivered to the
374 DH network will be around 134 GWh/y, of which 40% produced in cogeneration. Total heat losses on the
375 network were estimated to be around 16% of the thermal energy produced.

376 For the calculation of the thermal energy demand of buildings, the model described in section 2.1 was used
377 for the period 2011-2016. The application of this model yielded a value of specific energy consumption of
378 175 kWh/m². This value was reduced to 165 kWh/m² to keep into account a 1.2% reduction rate of
379 consumption per year thanks to refurbishment interventions in the period 2011-2016. Subsequently, for
380 estimating the reduction of energy consumption in the period 2016-2030, data from the regional Energy and
381 Environmental Plan of Piedmont were used. In this Plan, the expected reduction of energy consumption in
382 residential buildings for heating purposes, in the period 2016-2030, is 19.9%. The value of 165 kWh/m² was
383 thus further reduced by 19.9%, obtaining 132 kWh/m². This latter value was considered to be the
384 representative specific energy consumption of buildings in 2030. In the absence of a municipal energy plan,
385 the annual electricity demand of residential buildings was calculated considering a specific consumption of
386 27 kWh/m² of floor area, equal to that of Turin.

387



388

389 **Fig. 4** Extension of the DH network in Asti

390

391 **3. Results**

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

396 3.1 Energy and emission balance

397 The energy balance of the three case studies is reported in Figures 5 to 7. In each figure, the energy
398 consumption for thermal energy and electricity production was calculated. The operating configuration
399 considering the presence of a DH network was compared with a scenario where the DH network was not
400 present, based on the same amount of net energy provided to the final users. Total primary energy
401 consumption, CO₂ emissions, and pollutants emissions of the system are reported in Table 2. Primary energy
402 saving is between 7% (Asti) and 25% (Reggio Emilia). CO₂ emissions are reduced of 4.6% and 23% in the case
403 of Turin and Reggio Emilia respectively, while a 1% increase is found in the case of Asti. The reduction of NO_x
404 emission is between 54% (Asti) and 76% (Turin). The reduction of CO emission is between 46% (Asti) and 90%
405 (Reggio Emilia). The reduction of TSP emission is between 44% (Asti) and 87% (Reggio Emilia).

406 3.2 Pollutants concentration

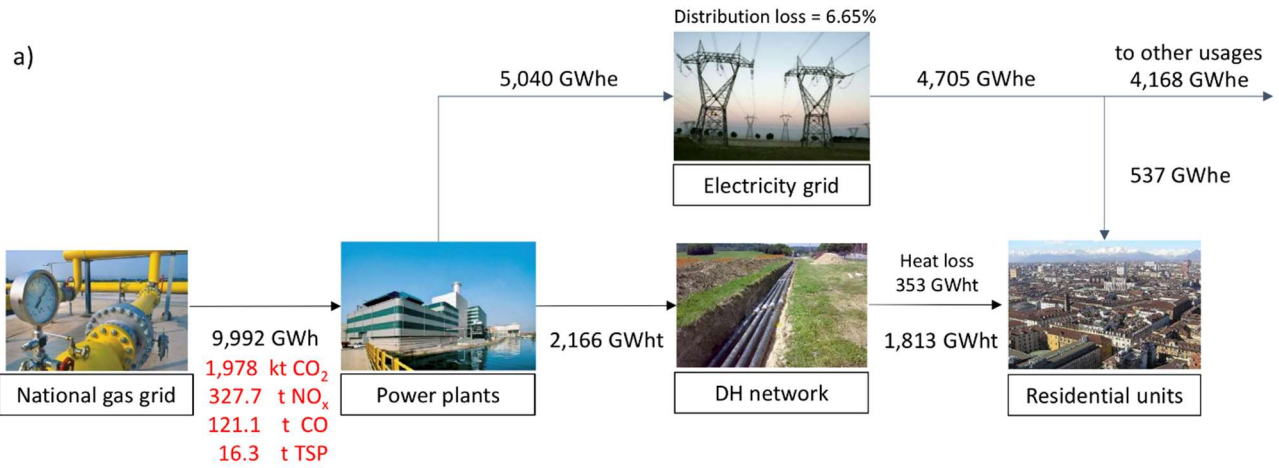
407 The comparison of operating scenarios in terms of pollutant concentration is reported in Figures 8 to 10. The
408 concentration at ground level generated by the energy plants powering the DH network (case of DH installed)
409 and by the residential boilers (case of DH not installed) is reported in onset a and b of these figures
410 respectively. The concentration difference between the presence and absence of a DH network is reported
411 in onset c. Finally, the delta external health costs per inhabitant are reported in onset d. These figures show
412 that, for every pollutant, the concentration at ground level is significantly higher in the case of residential
413 installations (no DH network). Average NO_x concentration reduction in the urban area is between around 1
414 µg/m³ (Asti) and 3 µg/m³ (Turin and Reggio Emilia). Average CO concentration reduction in the urban area is
415 between around 1 µg/m³ (Asti) and 4 µg/m³ (Turin). Average PM_{2.5} concentration reduction is around 0.1
416 µg/m³ in Turin and Reggio Emilia, and 0.01 µg/m³ in Asti. PM_{2.5} concentration difference is not significant,
417 due to the low emission factor of both power plants and residential boilers (all the simulated plants are
418 fuelled by natural gas).

419 3.3 Health externalities

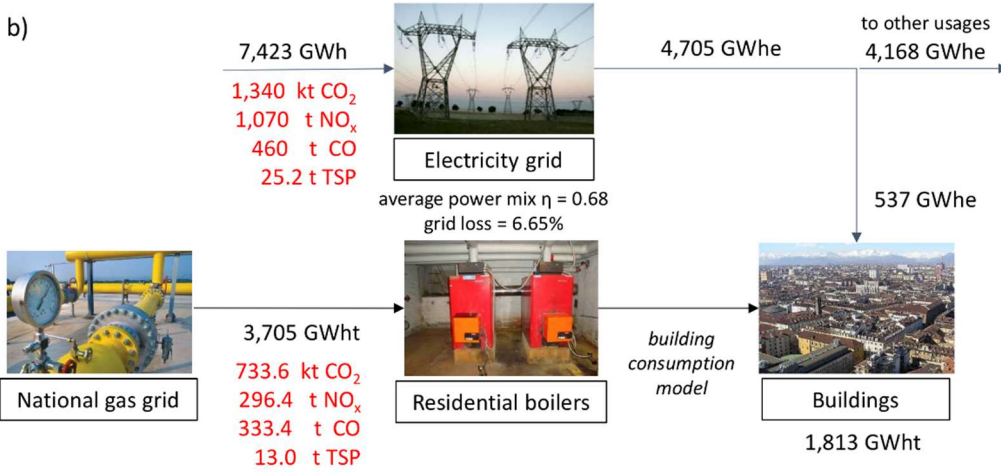
420 The estimates of the delta external health costs calculated by the DIDEM model show that, in general, the
421 installation of a DH network corresponds to a marked reduction of health externalities. This reduction is 3 –
422 10 €/inhabitant/y for Turin, 3 – 4 €/inhabitant/y for Reggio Emilia, and 1 – 2 €/inhabitant/y for Asti. In this
423 latter, an area is present where external costs are increased. However, this area is located outside the city
424 center, and delta external costs do not exceed 0.5 €/inhabitant/y. If delta external costs are summed over
425 the entire modelling domain and multiplied for the number of inhabitants, the total health externalities
426 reduction reported in Table 3 is found. This table also reports the characterization of uncertainties associated
427 to the method, that depend on i) the confidence level group on pollutant-outcome pairs (Group A and Group
428 A+B), and ii) minimum, mean and maximum value of the relative risk (slope of the CRFs). The results show
429 that total uncertainty is high. This is because the impact pathway methodology combines information from
430 different sources such as pollutant exposure, population data, and CRFs. Each of these sources carries with
431 it some degree of uncertainty, that affects the final cost estimate.

432

433



434

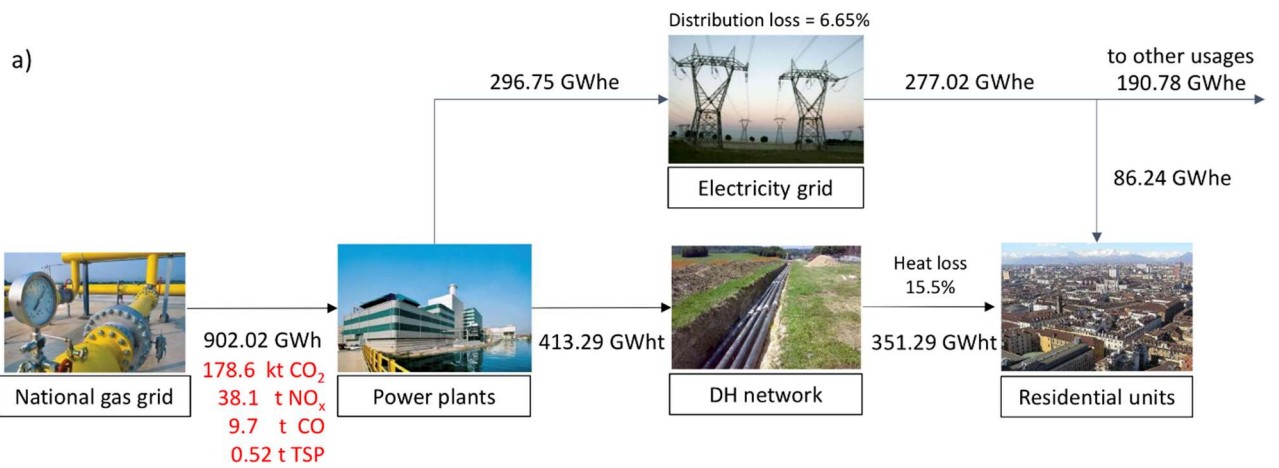


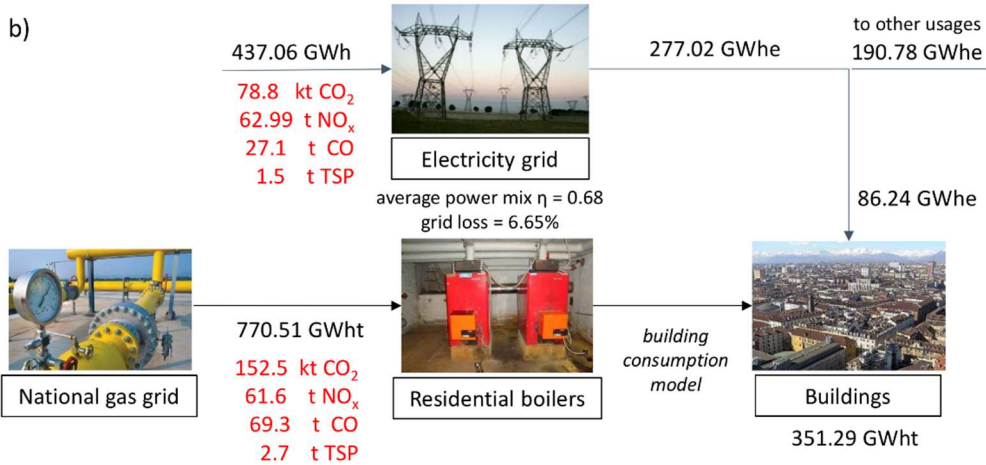
435 **Fig. 5** Energy and emissions balance with (a) and without (b) DH network in Turin

436

437

438

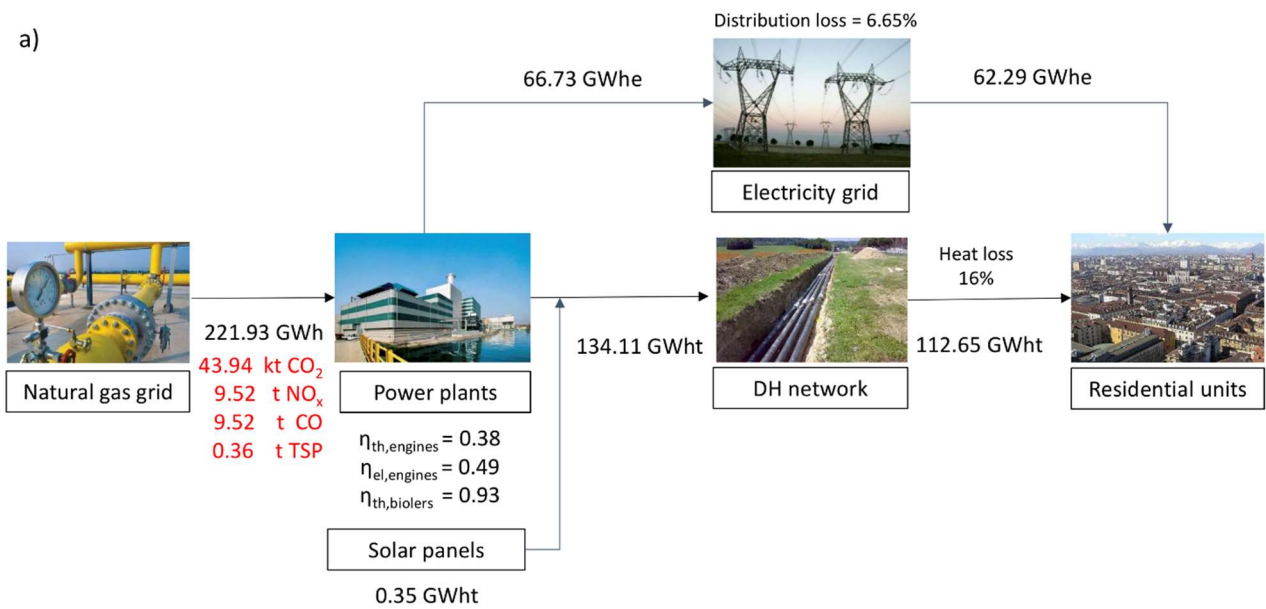




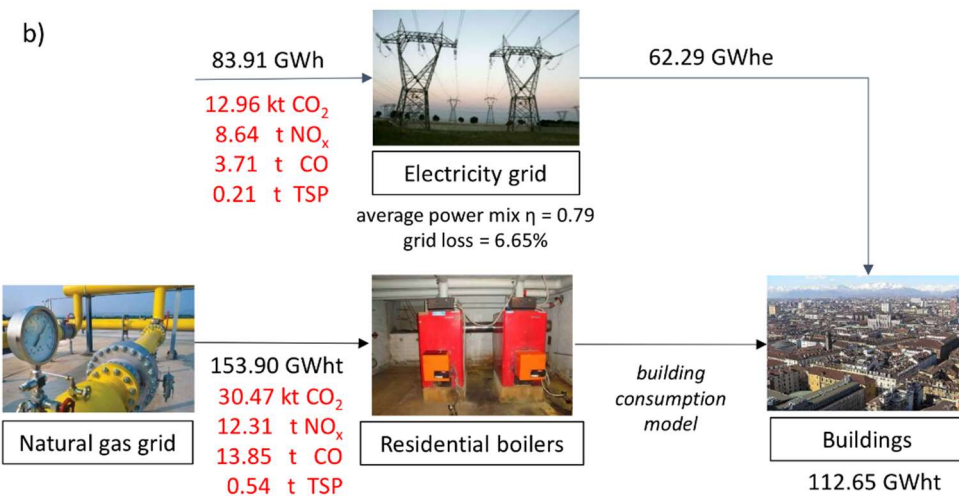
439

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

441



442



443

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

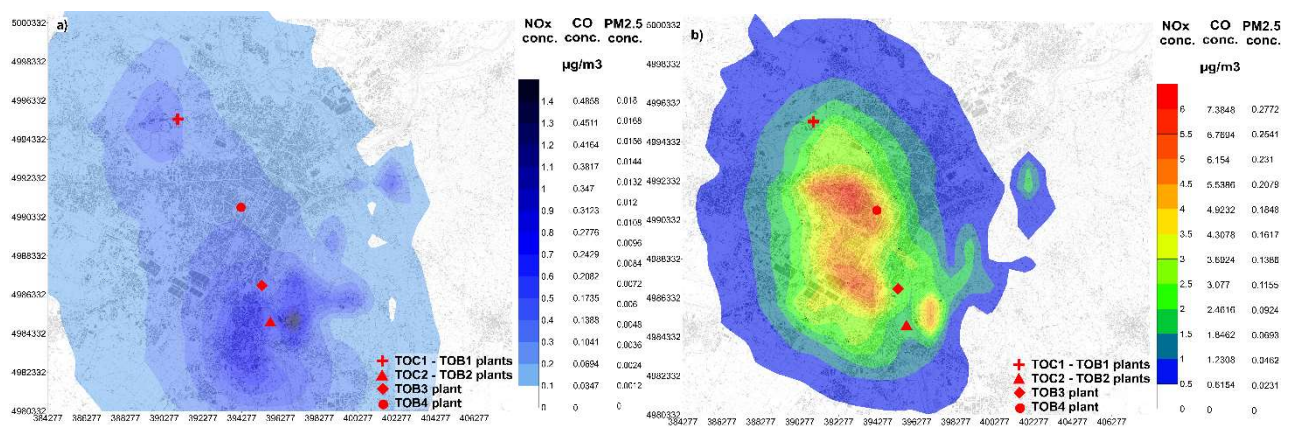
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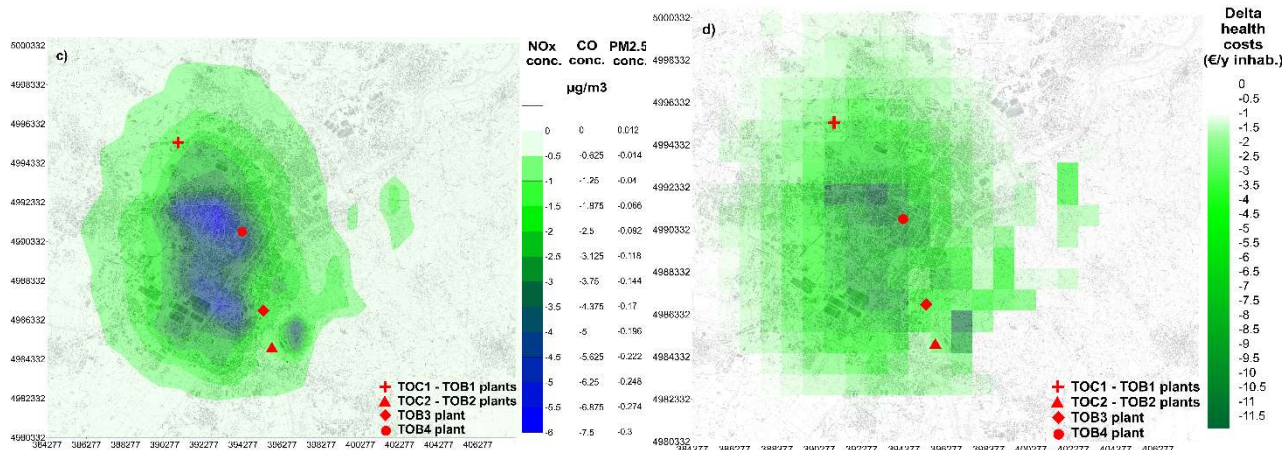
Table 2. Calculation of energy and emissions savings connected to the presence of a DH network in the three towns considered in the study.

		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%)

448



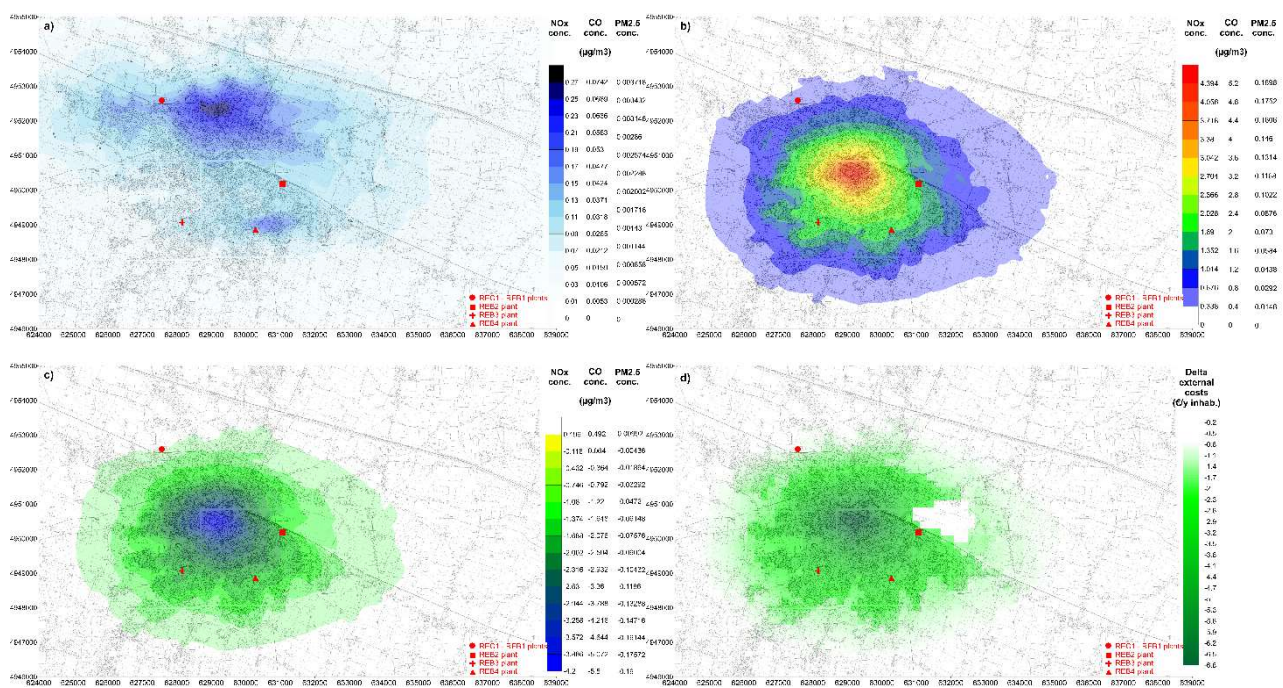
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450

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

457



458

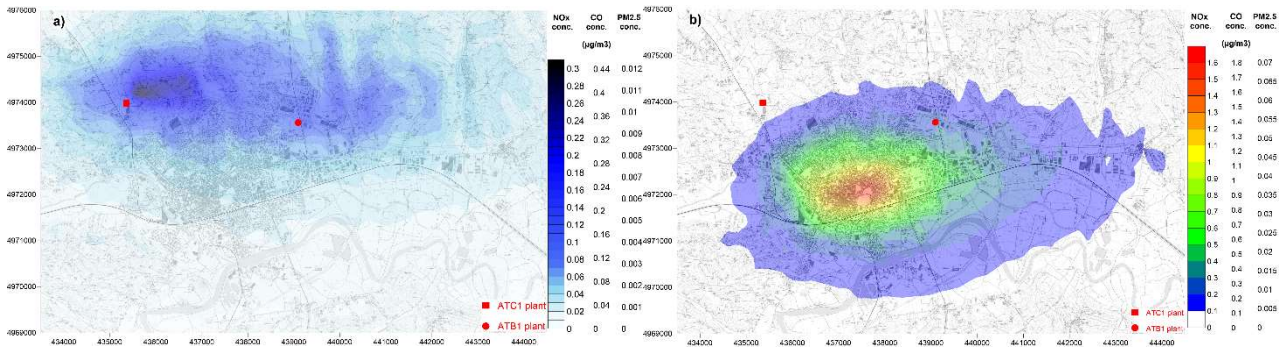
459

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

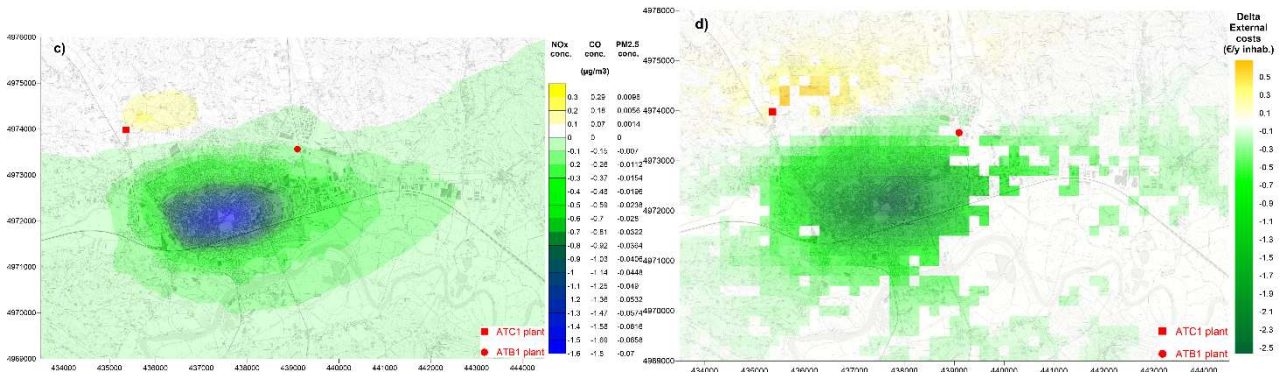
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469



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

476

477 Table 3. Total delta external health costs (difference between presence and absence of a DH network) in the
 478 areas of study, calculated with the DIDEM model. Characterization of uncertainties depending on i) the
 479 confidence level group on pollutant-outcome pairs (Group A and Group A+B), and ii) Minimum, mean and
 480 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

481

482 3.4 Comparison of the results

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

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

495

496 3.4.1 Average emission factors of the DH system (EF_{DH}).

497 The average emission factors of the DH system (EF_{DH}) were calculated as the sum of the pollutant emissions
498 of all power plants divided by total primary energy consumption. The results show that EF_{DH} is related to the
499 size of the system. EF_{DH} is, in general, higher for smaller systems and vice-versa. This is an expected result,
500 since, in general, centralizing power production brings lower energy consumption and more efficient
501 pollutant abatement systems (Calise et al. 2018). These values are also influenced by the amount of energy
502 produced in cogeneration, which is higher in Turin than in Asti. EF_{DH} is, in general, lower than EF of residential
503 boilers (cf. section 3.1). NO_x emission factor is between 32.7 kg/GWh and 42.9 kg/GWh. CO emission factor
504 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.

505

506 3.4.2 Specific emissions reduction (per capita or per residential volume) installing a DH network (ΔER_p and 507 ΔER_v).

508 Emissions reduction per capita (ΔER_p) was calculated dividing the emissions reduction (Table 2) by the
509 number of people living in the municipality. Emissions reduction per volume (ΔER_v) was calculated dividing
510 the emissions reduction (Table 2) by the residential volume connected to the DH network. These two
511 indicators provide slightly different information. The first shows the average emissions reduction in the entire
512 municipality, thus it indicates the environmental benefit for all the residents. The values of ΔER_p are 0.15 –
513 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
514 indicator is between a 0.38 t/inhabitant reduction (Reggio Emilia) and a 6.6E-03 t/inhabitant increase (Asti).
515 The second indicator (ΔER_v) is related to the only areas served by the DH network. The values of ΔER_v are 3.3
516 – 21.9 g/m³ (NO_x), 2.3 – 11.2 g/m³ (CO) and 0.08 – 0.4 g/m³ (TSP). For CO_2 , this indicator is between a 3.98
517 kg/m³ reduction (Reggio Emilia) and a 0.14 kg/m³ increase (Asti). The results show that these indexes mostly
518 depend on the efficiency of the proposed/replaced system, as well as on the assumptions made on emission
519 factors. The size of the system is also affecting the results. The higher is the share of the DH network, the
520 higher is the benefit for all the citizens. Similarly, the higher is the size of the network, the higher is the
521 reduction of contaminant per unit of residential volume connected.

522

523 3.4.3 Average and maximum NO_x concentration reduction in the municipality (ΔC_{ave} and ΔC_{max}).

524 Average NO_x concentration reduction in the municipality was calculated elaborating the results of dispersion
525 modelling with the software QGIS (Quantum GIS 2020) and MATLAB (Mathworks Inc. 2019). The only

526 pollutant NO_x was considered, provided that the concentration distribution was the same for all pollutants.
 527 ΔC_{ave} is 1.65 $\mu\text{g}/\text{m}^3$ in Turin, 0.28 $\mu\text{g}/\text{m}^3$ in Reggio Emilia, and 0.06 $\mu\text{g}/\text{m}^3$ in Asti. This parameter indicates the
 528 general concentration reduction in the considered area. If compared to the average annual concentration
 529 measured by fixed monitoring stations, it provides a preliminary estimate of the contribution of the DH
 530 system to air quality improvement. Average NO₂ concentration measured by monitoring stations in 2015
 531 was: 37 - 68 $\mu\text{g}/\text{m}^3$ in Turin, 40 $\mu\text{g}/\text{m}^3$ in Reggio Emilia, and 35 $\mu\text{g}/\text{m}^3$ in Asti (Piedmont Region Environmental
 532 Protection Agency; Emilia Romagna Region Environmental Protection Agency). Maximum NO_x concentration
 533 reduction (ΔC_{max}) is 5.63 $\mu\text{g}/\text{m}^3$ in Turin, 4.10 $\mu\text{g}/\text{m}^3$ in Reggio Emilia, and 1.53 $\mu\text{g}/\text{m}^3$ in Asti. The values show
 534 that, in some part of the town, higher concentration reduction are achieved. This depends on the position of
 535 the emission sources replaced by the DH network and, obviously, on the meteorological and geophysical
 536 conditions of the domain. The information gathered by analysing ΔC_{max} could be useful in view of the planning
 537 of a future network extension. Finally, these results show that the larger is the DH network, the higher is the
 538 ratio $\Delta C_{ave}/\Delta C_{max}$.

539

540 3.4.4 Specific concentration reduction (per capita or per residential volume) installing a DH network (ΔC_p and
 541 ΔC_v)

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

551

552 3.4.5 Specific health externalities reduction (per capita or per residential volume) installing a DH network
 553 ($\Delta \epsilon_p$ and $\Delta \epsilon_v$).

554 Average health externalities reduction per capita ($\Delta \epsilon_p$) and per residential volume ($\Delta \epsilon_v$) were calculated
 555 starting by the output of DIDEM model (Table 3). The values of delta-costs in the domain cells contained in
 556 the municipality were extracted with the software QGIS and elaborated with MATLAB. Average and range of
 557 $\Delta \epsilon_p$ values are reported in Table 4. The difference among the cases is significant, and shifts from 0.25
 558 €/inhabitant (Asti) to 8.25 €/inhabitant (Turin). From these results, it appears that the size of the system and
 559 population density affect significantly the externalities reduction. Average health externalities reduction per
 560 residential volume ($\Delta \epsilon_p$) was calculated dividing total externalities reduction (Table 3) by the residential
 561 volume connected to the DH network. $\Delta \epsilon_p$ is 0.043 – 0.972 €/m³, 0.004 – 0.061 €/m³, and 0.012 – 0.237 €/m³
 562 for Turin, Reggio Emilia, and Asti respectively. Surprisingly, $\Delta \epsilon_p$ value is greater in Asti than in Reggio Emilia.
 563 A possible explanation could be that, in Reggio Emilia, population exposure is lower in the areas where
 564 maximum concentration reduction occurs.

565

566 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
Emission reduction per residential volume installing a DH network (ΔER_v)	TSP		0.02	0.03	0.004
	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
Average NO _x concentration reduction in the municipality (ΔC_{ave})		$\mu\text{g}/\text{m}^3$	1.65	0.28	0.06
Maximum NO _x concentration reduction (1-hr annual average) in the municipality (ΔC_{max})		$\mu\text{g}/\text{m}^3$	5.63	4.10	1.53
Average NO _x concentration reduction per capita installing a DH network (ΔC_p)		($\mu\text{g}/\text{m}^3/10^6$ inhabitants)	1.90	2.07	0.79
Average NO _x concentration reduction per residential volume installing a DH network (ΔC_v)		($\mu\text{g}/\text{m}^3/10^6 \text{ m}^3$)	0.027	0.021	0.017
Average health externalities reduction per capita (Group A – Group A+B) ($\Delta \epsilon_p$)		€/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 ($\Delta \epsilon_v$)		€/m ³	0.043 – 0.972	0.004 – 0.061	0.012 – 0.237

567

568 3.5 Discussion

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

579 For GHG emission, the result reported in this study showed contrasting results. In the cases of Turin and
580 Reggio Emilia, the emission reduction trend extensively reported in the bibliography (e.g., Rezaie and Rosen
581 2012; Andrić et al. 2017) was confirmed. The CO₂ emission factor of DH systems was in line with the average
582 value reported by Noussan (2018), based on the study on 140 DH systems in Italy of different structure and
583 size (0 - 0.30 kg/kWh). In the case of Asti, a slight increase of GHG emissions was found. This result is strongly
584 affected by the precautionary assumptions made, both for building consumption (20% consumption
585 reduction based on 2015) and electricity production in 2030 (60% share of renewable sources). Nevertheless,
586 this result shows that, in the context of changing energy scenarios, future sustainability of DH systems will
587 be increasingly depending on their design, size and operational structure.

588 Comparing the alternative energy systems in terms of concentrations, a general concentration reduction was
589 found, in particular in the city center, and the areas served by the DH network. This is the result of replacing
590 relatively low and central multiple pollution sources (20 – 30 m) with higher de-centralized point sources (40
591 – 70 m). Although dispersion modelling is a consolidated activity, few studies are reported in the bibliography
592 concerning the comparative analysis of DH systems (Genon et al. 2009; van der Kamp and Bachmann 2015).
593 The results reported in this study show that DH networks also bring significant advantages in terms of health
594 impacts and costs reduction. This was reported in a previous study on the urban area of Turin (Ravina et al.,
595 2018b). This study confirms that a reduction of externalities is also expected for DH networks of lower size,
596 as in the cases of Reggio Emilia and Asti. The elaboration of the indicators reported in Table 4 tried to analyse
597 the relevant factors affecting the environmental performance of DH networks. If results are compared in
598 terms of specific emissions, it appears that the efficiency and emission factors of both the DH and the
599 replaced system mainly affect the results. Comparing existing networks, two other factors show a major
600 influence: the size of the network and the contribution of cogenerated energy to the system. Higher specific
601 pollutant reduction (per capita or per residential volume connected) are associated to larger networks.
602 Specific CO₂ reduction is more connected to the primary energy balance. Indicators based on specific
603 concentrations introduce different considerations, as these only consider the air quality in the municipality
604 and do not account for the electricity balance. In this case, the size of the network has still a major influence.
605 Dispersion conditions, thus specific meteorology and geography of the area, also affect the results, as the
606 higher value of ΔC_p in Reggio Emilia than Turin shows. Finally, if the comparison is done in terms of
607 externalities reduction, results still depend mainly on the DH network size, but other factors appear, such as
608 population density and geographical distribution of pollutants concentration. For these reasons, average
609 health externalities reduction per capita ($\Delta\epsilon_p$) and per residential volume ($\Delta\epsilon_v$) seem to provide more
610 complete information on the final impact of the alternative solutions on the final receptor (i.e. the resident
611 population). In a previous study (Ravina et al. 2019), the authors analysed the application of models for the
612 calculation of health damage externalities, highlighting that these tools can provide valuable support for the
613 selection of the most environmentally and socially sustainable alternative of implementation. Given these
614 considerations, the application of indicators based on health externalities for the evaluation of DH systems
615 ($\Delta\epsilon_p$ and $\Delta\epsilon_v$) could be the object of future investigation.

616

617 **4. Conclusion**

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

625 currently facing the challenge of becoming thermal smart grids, with similar opportunities and risks of the
626 better-known electric smart grids.

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

638

639 **Conflict of interest**

640 The authors declare no conflict of interest.

641

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