Available online at www.sciencedirect.com

ScienceDirect

Energy Reports 7 (2021) 449–457

www.elsevier.com/locate/egyr

17th International Symposium on District Heating and Cooling, Nottingham Trent University, September 6th–9th 2021, Nottingham, UK

Synergies between buildings retrofit and district heating. The role of DH in a decarbonized scenario for the city of Milano

Marianna Pozzi*, Giulia Spirito, Fabrizio Fattori, Alice Dénarié, Jacopo Famiglietti, Mario Motta

Department of Energy– Politecnico di Milano, Via Lambruschini 4 – 20156 Milano, Italy

Received 30 July 2021; accepted 7 August 2021

Abstract

The goal of this work is to present challenges and opportunities for the development of 4th generation district heating in future decarbonized scenarios for the Italian city of Milano. The work has been developed in the framework of a Climate-KIC project to support Milano municipality in developing decarbonization measures. The first part of the work consists in the evaluation of a geographical distribution of the civil sector heat demand according to a bottom-up approach based on open data. Thanks to this statistical tool, also buildings retrofit can be analysed. Three retrofit scenarios are simulated according to policy goals for 2030 and 2050, foreseeing a retrofit priority of worst energy performances buildings, resulting in 8.8TWh, for the first two scenarios, and 9.4TWh for the last one. The areas characterized by the majority of retrofit can be identified as the most suitable for low temperature district heating development. Renewables and low temperature waste heat sources are also assessed, resulting in 9.8TWh of available heat. The application of district heating in combination with the identified renewables is assessed in these scenarios with a clustering approach. The evaluation of potential diffusion of 4GDH is based on the comparison between the overall cost of district heating and the competing individual systems costs: district heating is considered feasible only in retrofitted buildings where district heating cost is lower than individual systems cost (about 0.7TWh in each scenarios). The retrofitting scenarios combined with the diffusion of renewable based 4GDH are assessed also in terms of environmental impact. The current greenhouse gas emissions related to the actual heating systems, evaluated through the Thermal Systems Regional Cadastre database, is compared to the district heating development scenarios and to individual heat pump system scenarios. The results show the highest reduction of emission in the district heating scenarios (65%).

Peer-review under responsibility of the scientific committee of the 17th International Symposium on District Heating and Cooling, 2021.

Keywords: Heat demand; Map; Retrofit scenarios; Fourth generation district heating; Greenhouse gas emissions

---

1. Introduction

In Europe buildings are responsible for about 40% of the final energy consumption and for about 36% of the CO_2 emission [1]. 35% of the Italian buildings stock is made up of buildings built before 1970 [2] and about 75%

---

* Corresponding author.
E-mail address: marianna.pozzi@polimi.it (M. Pozzi).

https://doi.org/10.1016/j.egyr.2021.08.083

Peer-review under responsibility of the scientific committee of the 17th International Symposium on District Heating and Cooling, 2021.

is thermally inefficient [1]. In particular, in the residential sector about 75% of the energy consumption is due to the dispersion through the envelope [3].

Beside envelope insulation and heating systems substitution (possibly with renewable energy sources), district heating (DH) would be a further interesting option to reach those targets since it can improve the modulation of heat generation and can enable recovery of waste heat [4], whose heat would otherwise be wasted. The convenience of DH however depends on the relative distance between sources and demands and on the spatial density of demand. Therefore, assessing the potential of DH needs a good knowledge of spatial distribution of demand and sources. In future, heat demand density is expected to decrease as consequence of the buildings retrofit; this translates in the need of analysing future scenarios, to evaluate the profitability of DH, in particular the 4th generation DH (4GDH) [5]. This need is due to the question about profitability of DH if heat demand density reduces.

Therefore, the aim of this work is to show that it is possible to create synergy between DH diffusion and the buildings retrofit if these two measures are coherently planned considering spatial aspect and not only prioritizing worst performing buildings. This work is developed in a framework of a Climate KIC funded project, Deep Demonstration Milano, aimed at supporting the local municipality in developing decarbonization measures. Within this context, the final goal is to identify most interesting areas for 4GDH diffusion in refurbishment scenarios. The novelty of this work lies in using clustering approach to identify areas in which retrofit and diffusion of 4GDH are synergic. The diffusion of 4GDH is also compared to the individual heat pump solution in retrofitted buildings under the greenhouse gas emission point of view, to show the environmental benefit of the DH system application.

In literature is possible to find several works about the current heat demand or the future heat demand evaluation and the development of district heating in different cities and countries. One of the strengths of this work is the use of only open data for the evaluation of heat demand distribution at census cells level; for residential sector the analysis starts from Energy Performance Certification (EPC) database that is widespread to evaluate buildings energy consumption in region which provides this database as open data, but EPC database does not cover all the building stock. Dall'O' et al. in [6], like [7], use EPC to create indicators to evaluate different retrofit scenarios, considering construction ages, type of buildings aggregation and buildings conditions (already retrofitted or not). In this paper some retrofit scenarios are simulated according to National Energy Climate Plan (NECP) [8] and Long-Term Strategy (LTS) [9] estimations about deep renovated floor area respectively until 2030 and 2050. To achieve the important energy savings and greenhouse gas emission reduction according to NECP and LTS, it is necessary to combine buildings retrofit to the replacement of heating systems with more efficient system that exploit renewable energy, like 4GDH. The potential of 4GDH at large-scale has never been computed before in an Italian context but only 3rd generation DH (3GDH) in a current scenario, as in Heat Roadmap Europe 4 [10], Hotmaps [11] project and the Italian study [12]. Studies on 4GDH can be found in countries as Sweden, Denmark and Finland that demonstrate the potential of low-temperature district heating in future market [13,14] and the use of heat pump powered by ambient heat in DH network [15–18]. Spirito et al. in [19] conducted a preliminary analysis on the 4GDH development, without considering synergy between retrofit and DH systems diffusion.

The add value of this work is the possibility to create a synergy between the municipality decarbonization measures and the development of 4GDH systems, identifying the most interesting areas under this point of view in the case study of Milano.

2. Methodology

In this section the structure and the methods used in the work are explained. The work is divided into four parts:

1. *Geographical distribution of civil sector heat demand*: starting from available data about EPC or Census dataset, a method is implemented to distribute heat demand at census cells level.
2. *Buildings retrofit*: according to NECP and LTS estimations about retrofitted floor area respectively until 2030 and 2050, three retrofit scenarios, based on different starting conditions, are analysed.
3. *4GDH potential*: starting from buildings retrofit scenarios and considering only retrofitted census cells where DH system costs are lower than individual systems costs, 4GDH potential is evaluated.
4. *Greenhouse gas emission*: a comparison between greenhouse gas emission related to DH systems and individual systems are evaluated.

In the following sections, the methodology used in each part of the work is explained.

2.1. Geographical distribution of civil sector heat demand

The first part of this work focuses on the geographical distribution of heating and domestic hot water (DHW) demand for civil sector for the Italian city of Milano. The heat demand available data refers to 2013. Due to the different available data, analysis is different between residential and tertiary sector heat demand.

A statistical model based on a bottom-up approach starting from the open data of the Italian Building Census database, ISTAT [2], and the EPC database, available on CENED website [20] is developed for the residential sector heating demand. The average heating demand and the net floor area are extrapolated from EPC database for residential sector considering different buildings categories: type of buildings, single-houses or apartment block, and construction ages. The heat demand of the buildings' categories is calculated according to the thermal dispersion through the envelope, so proportional to the thermal transmittance of the envelope's components j (U_j), to the area of the envelope's components j (A_j) and to the temperature difference between inside (T_{int}) and outside (T_{ext}) (2013) during the heating period (N) , over the floor area ($S_{building}$) as in the equation in Fig. 1 (where $\Delta t = 1h$). Heating demand in each census tracts is calculated multiplying the floor area of residential buildings available in the national census database provided by ISTAT [1,2] and the corresponding specific heating demand is reported in Fig. 1.

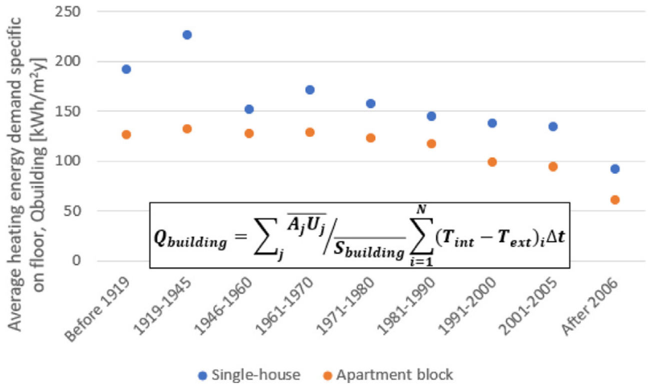


Fig. 1. Average heating energy demand specific on floor for single-house and apartment block and the used equation.

Another residential sector's heat need is due to domestic hot water demand. Specific DHW demand is considered equal to 444.1 kWh/(inhab. year), calculated from [21] considering a system efficiency equal to 80%, and the total resident population, available on the ISTAT dataset [2]. Multiplying the specific DHW demand to the resident population in each census cells provided by ISTAT dataset, DHW demand in each census cells is calculated.

Civil sector is also made up of the tertiary sector made up of public administration, hospitals, hobby, schools, hotels, sport, offices, stores and other with very different heating energy demand due to occupants needs. The analysis starts considering regional heat demand for space heating and DHW estimated by a Hotmaps project [22], equal to 17.9 TWh/year in 2013; this is divided into the different sub-sectors' heat consumption according to the incidence of national sub-sectors space heating consumptions from GSE's report [21] with an estimated system efficiency of 90%. Evaluating the incidence of each sub-sector on the total tertiary demand using GSE data, Hotmaps heat demand. By knowing the number of employees provided by ISTAT [2] for each sub-sector, the specific heat demand for employee is calculated. Values are shown in Fig. 2 and are used to calculate tertiary sub-sectors heat demand in each census tracts by multiplying these values to the corresponding number of employees for every census area.

2.2. Buildings retrofit

Thanks to the statistical tool also buildings retrofit can be analysed. Three different retrofit scenarios are analysed, excluding from the retrofit all the building built before 1945 due to the possible historical constrains which they are subjected. There are a lot of other barriers to buildings retrofit as knowledge-based barriers, economic barriers and political barriers [23], but due to the difficulty of their implementation in the scenarios, they aren't considered.

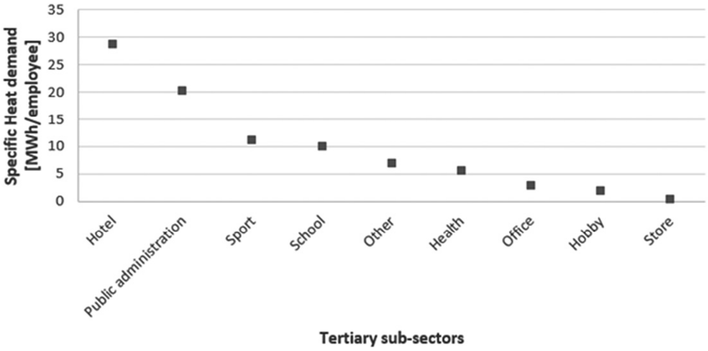


Fig. 2. Factors used for tertiary sector heat demand distribution [MWh/employee].

These historical buildings which cannot be easily refurbished nor integrated by renewables are very suitable for a connection to the existing 3GDH and are therefore not considered in 4GDH analysis.

The following scenarios are applied to residential buildings, achieving the policies goals of about 0.7% of annual retrofitted residential floor area until 2030 [8] and 1.6% of annual retrofitted residential floor area until 2050 [9]. The same percentages are applied to tertiary buildings heat demand due to the missing data about tertiary floor area. Deep renovation of buildings is here considered, resulting in about 60% energy reduction of retrofitted residential buildings [24] with a minimum reachable consumption of 45 $\text{kWh/m}^2_{\text{(floor)}}\text{y}$. Three refurbishment scenarios are analysed according to 3 different selection criteria for buildings to be refurbished:

1. *Scenario 1 — Diffuse refurbishment*: retrofit of residential buildings in census cells with a specific heating demand higher than the average city value equal to 127 $\text{kWh/m}^2_{\text{(floor)}}\text{y}$.
2. *Scenario 2 — Refurbishment in areas with 3GDH potential*: retrofit of residential buildings in census cells with an average specific heating demand higher than 127 $\text{kWh/m}^2_{\text{(floor)}}\text{y}$ located in areas identified as suitable for potential diffusion 3GDH [12].
3. *Scenario 3 — Refurbishment in high density areas*: retrofit of residential buildings in census cells with an average specific heating demand on floor area higher than 120 $\text{kWh/m}^2_{\text{(floor)}}\text{y}$ and an average density of heat demand higher than 0.1 $\text{kWh/m}^2_{\text{(cell)}}\text{y}$.

Even if the scenarios follow different approach, they allow to retrofit the same quantities of floor areas.

DHW demand is always the same after retrofit and any reduction of this part of heat demand is considered.

2.3. 4GDH potential

Regarding the three scenarios, overall heating demand in each census cell interested by refurbishment can be met by a DH system; a centralized heating system in every retrofitted building is assumed, so 100% of retrofitted buildings can be met by a DH system. Moreover, only 25% of retrofitted buildings is assumed with a centralized system for DHW preparation. Eq. (1) allows to estimate the heat demand connectable to a DH network in each census cell (Q_{DHi}), considering residential heating demand (Q_{SH,r_i}), residential DHW demand (Q_{DHW,r_i}) and tertiary heat demand (Q_{TER,r_i}) in retrofitted buildings.

$$Q_{DHi} = Q_{SH,r_i} + Q_{DHW,r_i} \cdot 0.25 + Q_{TER,r_i} \left[\frac{\text{Wh}}{\text{year}}\right] \tag{1}$$

To evaluate the suitability of DH system in retrofitted buildings, it is necessary to estimate the investment and operating cost, related to the heat distribution network potentially built and to the sources potentially used in future scenarios. The overall DH system cost is assessed as the sum of the distribution capital cost, the operating and pumping cost, the substation cost and the sources related cost.

- *Distribution capital cost (C_d)*: Persson and Werner in previous works [25–27], defined a parametric curve to relate effective width and the plot ratio used to define linear heat density. Due to the available data, another correlation to evaluate linear heat density is used, considering effective width (w) as function of the building ratio (n_b) (for further details please refer to [28]). Distribution capital cost depends to the annuity (a, equal to 0.05), the pipe diameter (d_a), the size-independent construction cost constant (C_1, estimated equal to 663 €/m for 4GDH [19]), the construction cost coefficient (C_2, estimated equal to 1596.3 €/m^2 for 4GDH [19]), the linear heat density (Q/L) and a factor that considers the connection cost to the network (c, equal to 1.2); through Eq. (2) distribution capital cost is calculated:

$$C_d = \frac{a \cdot (C_1 + C_2 \cdot d_a) \cdot c}{Q/L} = \frac{a \cdot (C_1 + C_2 \cdot (0.0486 \cdot \ln (Q/L) + 0.0007)) \cdot c}{Q \cdot w(n_b)} \quad \left[\frac{\text{€}}{\mathrm{Wh}}\right] \tag{2}$$

- *Pumping cost (C_p)*: this cost considers the operating cost due to pumping. The energy consumed for pumping is assumed about 5% of the energy injected into the network ($Q_{injected}$, considering distribution losses and heat demand) and the electrical cost associated to pumping, $c_{el,pump}$, amounts to 107 €/MWh. (For further details please refer to [12]). This cost is evaluated according to Eq. (3):

$$C_p = Q_{injected} \cdot 0.05 \cdot c_{el,pump} \ [\text{€}] \tag{3}$$

- *Substation cost*: it is the investment cost required for the installation of the substations. According to the data from the existing network, it is considered equal to 39.5 €/MWh in single houses and to 7.1 €/MWh in multi-family houses.
- *Source cost*: heat sources, as industries, metro stations, datacenter and wastewater treatment plans and ground water heat pumps, are first mapped and related cost are evaluated. In this work an average value of the cost related to the investment and the use of source is considered: 56.5 €/MWh (Please refer to [12] for further details).

The total cost related to the DH system is compared to the cost related to the individual solution. We assume as individual solution in retrofitted buildings only electrical heat pumps with a cost equal to 109.9 €/MWh [29], calculated as an average value weighted on number of single houses and multi-family houses. In this way we exclude all the cells where DH system cost is higher than individual solution cost.

The remaining demand is aggregated through a density-based clustering algorithm, called DBSCAN (Density-Based Spatial Clustering of Application with Noise), as in [12], so demand is grouped not only to the intensity of the heat demand but also to their spatial proximity. This step allows to identify the most suitable region for district heating development and/or installation, from a technical and economic point of view and based on their geographical position. The clustering approach groups together only the points that satisfy a density criterion, defined as a minimum number of objects (*MinPts, n*) within a cut-off radius (*Eps, ε*). In this work n is considered equal to 2 and ε equal to 0.09. For further details about the definition of the two parameters please refer to [12].

2.4. Potential impact on climate change

The suitability of DH is also evaluated assessing the potential impact on climate change. For the evaluation, the DH system was compared with a vapour compression heat pump (groundwater source), for now on also referred as "heat pumps", considered as alternative appliance. The carbon footprint of the two energy systems was assessed with life cycle approach, using Ecoinvent 3.6 [30] as background database and IPCC 2013 — 100 years [31] as characterization method (please refer to [32] for further details). The activity data used for the evaluation are summarized as follows.

- *District heating*. A 4GDH network was supplied by a groundwater heat pump (for 65%, with a seasonal coefficient of performance — SCOP equal to 4.5 pumping included and a capacity of 4 MW), a solar thermal array (for 10%, 3 000 m^2 with producibility equal to 900 kWh$_{\mathrm{th}}$/m^2, considering a storage of 300 m^3), and a 3GDH as backup (for 25%). The 3GDH was composed by 22% of boilers, 46% of combined heat and power plants, 21% of waste to energy plant, and 10% of industrial heat recovery [19]. The heat losses were assessed equal to 10% and 12% for 4GDH and 3GDH, respectively.
- *Heat pump*. SCOP (4.0 pumping included), power (80 kW), and storage volume (100 l).

For both, the environmental profile of the electricity used for the thermal energy production was assessed considering the Italian target, at 2030, devised in the Integrated NECP.

In order to make a fully indicative evaluation of the potential decarbonization pathway, the two solutions described were compared to the current energy systems (natural gas, oil, Liquid Petroleum Gas, wood boilers, etc.). These technologies were assessed consulting the data of the Thermal Systems Regional Cadaster database [33] and the Ecoinvent database.

3. Results and discussions

In this section the results of the methods explained in the previous chapter are shown.

Fig. 3 shows the results of the civil sector heat demand distribution at census cells level for the Milano municipality: total heat demand is 11.3 TWh, divided into 7.1 TWh for residential sector and 4.2 TWh for tertiary sector. The highest demand density is in the city centre, due to the great population density and to the tertiary sector buildings presence. Comparing residential sector heating demand with measured data, only about 5% error is obtained.

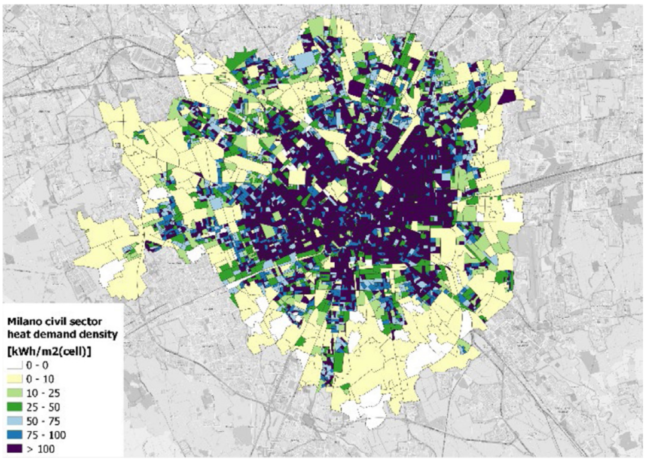


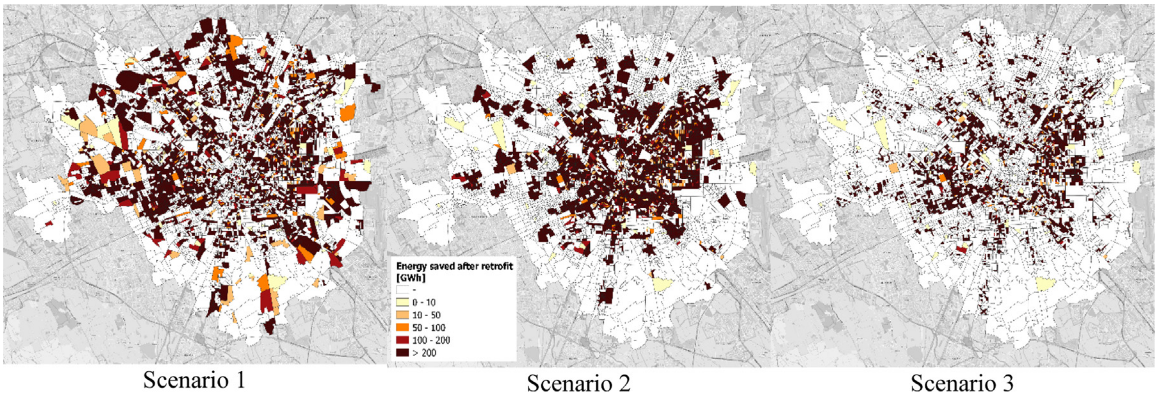
Fig. 3. Civil sector heat demand density in each census cell [kWh/$m^2_{(cell)}$].

Fig. 4 shows the energy saved between the current scenario and the three building retrofit scenarios. Scenario 1 allows to obtain 22% of energy saving, Scenario 2 reaches 23% of energy saving, instead Scenario 3 only 17% (total heat demand after retrofit is: 8.77 TWh in scenario 1, 8.76 TWh in scenario 2 and 9.4 TWh in scenario 3). The total heat demand only in retrofitted buildings is 1.92 TWh in scenario 1, 1.90 TWh in scenario 2 and 1.47 TWh in scenario 3. In term of energy savings, scenario 1 and scenario 2 obtain the same result but Fig. 4 shows a very different interested area due to the different starting assumptions that allow to retrofit different number of census cells and buildings. Scenario 1 has a quite homogeneous refurbishment in the whole city, instead scenario 2 and scenario 3 focus the retrofit on the cells located in the city centre (scenario 2) and in the area adjacent to the centre (scenario 3).

The heat demand technically connectable to DH network is calculated by Eq. (1), resulting in: 1.74 TWh in scenario 1, 1.75 TWh in scenario 2 and 1.32 TWh in scenario 3.

The costs related to DH system are also evaluated for the census cells interested to refurbishment, to compare them to the individual heat pump system cost (average DH cost is 80.1 €/MWh in scenario 1, 80.2 €/MWh in scenario 2 and 77.8 €/MWh in scenario 3). Fig. 5 shows the distribution cost of DH system in the three retrofit scenarios compared to a constant individual heat pump system cost; every census cell with DH system cost higher than individual heat pump system cost are excluded to the clustering because DH is not profitable; this results in 1.66 TWh for scenario 1, 1.69 TWh for scenario 2 and 1.31 TWh for scenario 3 of technical and economic potential of DH (respectively the 86%, 89% and 89% of the total retrofitted buildings demand).

Fig. 6 shows the results of clustering in the three retrofit scenarios. Some differences can be noticed: number of clusters is 45 in scenario 1, 56 in scenario 2 and 68 in scenario 3; scenario 3 has very dispersed clusters and more



Scenario 1 Scenario 2 Scenario 3

Fig. 4. Energy saved after buildings retrofit in three different scenarios [GWh/y].

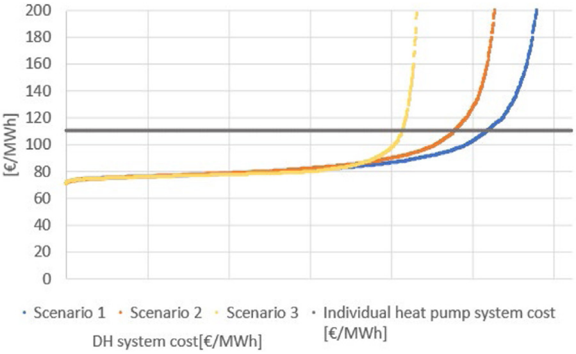
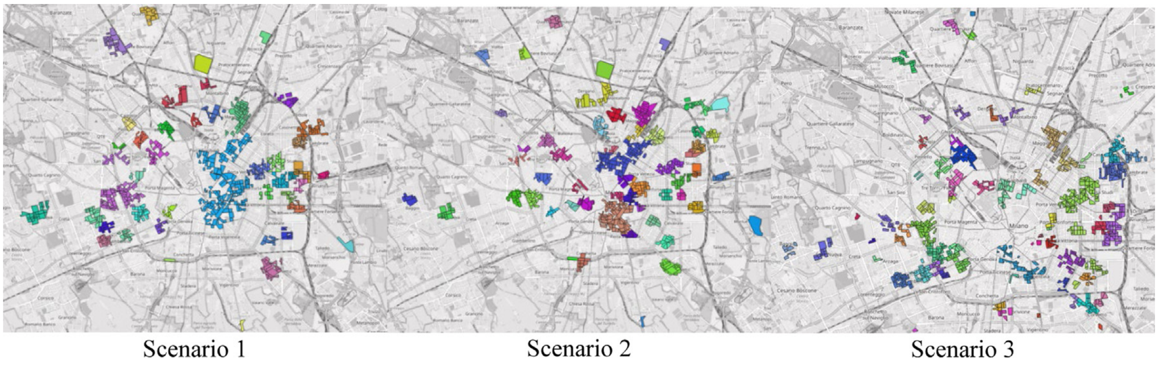


Fig. 5. DH system cost vs. individual heat pump system cost in retrofitted census cells [€/MWh].



Scenario 1 Scenario 2 Scenario 3

Fig. 6. Identified clusters in the three different retrofit scenarios.

little compared to scenario 1 and scenario 2, this is a negative feature for a development of a new DH network in which closed clusters are much profitable. The total clustered heat demand resulting from clustering is: 0.71 TWh in scenario 1, 0.76 TWh in scenario 2 and 0.69 TWh in scenario 3 (respectively the 37%, 40% and 47% of the refurbished demand).

Fig. 7 shows the comparison among the DH and the alternative energy systems in terms of CO_2eq emissions. The environmental profile assessed is 98 gCO_2eq/kWh_{th} for DH, 104 gCO_2eq/kWh_{th} for the heat pump and 281 gCO_2eq/kWh_{th} for natural gas, 337 gCO_2eq/kWh_{th} for oil, 51 gCO_2eq/kWh_{th} for wood boiler, 351 gCO_2eq/kWh_{th}

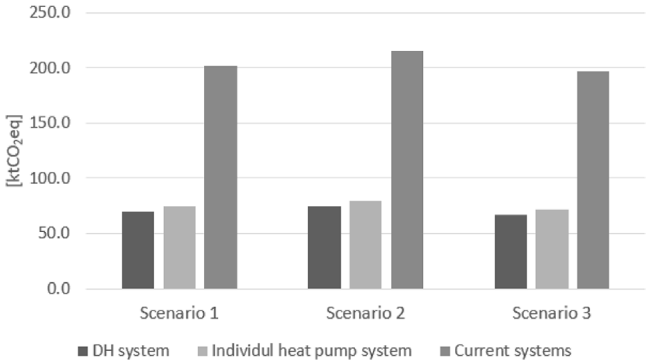


Fig. 7. Comparison between CO_2eq emissions related to DH or individual heat pump system in clustered cells [ktCO_2eq].

for Liquid Petroleum Gas current technologies. As reported, the emissions decreased by 2% and 65% comparing the DH with the heat pump and the current systems.

The clustering approach allows to identify the priority areas to focus retrofit and DH synergy. The remaining areas can be interested to retrofit and heat pump synergy, due the little difference between DH and heat pump system emission. Moreover, the three scenarios allow to reach different geolocation of clusters interested by DH. Scenario 3 follows a refurbishment criterion often used in decarbonization scenarios, i.e. high density areas retrofit. In DH development, this scenario allows to obtain negative result because cluster are little and dispersed in the whole city. Scenario 1 and scenario 2 allow to achieve similar results but scenario 2 is preferable from the demand served by DH system and the cluster distribution point of view.

4. Conclusions

The goal of this work is to present challenges and opportunities for the development of 4GDH in future decarbonized scenarios for the Italian city of Milano. The analysis is conducted starting from geographical distribution of civil sector heat demand using only open data, this is a crucial point because EPC data has to be reduced due to a lot of strange values. In this work also different retrofit scenarios are analysed and some difference in the results can be noticed in term of energy savings (17%–23%) and clustered heat demand (37%–47% of the refurbished demand).

To evaluate CO_2eq emission, a life cost approach is used. This approach referred to 2030 environmental profile of electricity devised in NECP, instead retrofit scenarios referred to 2050. At 2050 an hydrogen penetration and a different electricity environmental profile is expected, so the work could be improved considering the development of energy system.

Analysing retrofit scenarios, results show that cells interested by 4GDH systems are not the same of 3GDH systems [12], in fact clusters are smaller and dispersed. Scenarios allow to identify areas more interested to DH development and, in view of the development of 4GDH within the city, it is important to think about a retrofit of those area, creating synergy between DH and retrofit.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The work has been developed in the framework of the project “DDMI, Deep Demonstration Milano” funded by Climate-KIC, Italy to support Milano municipality in developing decarbonization measures. The authors gratefully acknowledge the Milano municipality and AMAT that have provided the important inputs for the analysis.

References

[1] Bertelè U, Chiesa V. Smart Building Report - Il volume d'affari, ed i modelli business degli operatori. 2020.
[2] ISTAT - Istituto Nazionale di Statistica n.d. http://dati.istat.it/.
[3] Conti C, Rossetti M, Padovan G. Ruolo dell'isolamento termico nel contenimento dei consumi energetici - Evoluzione e innovazione dei materiali e sistemi di isolamento termici in edilizia. 2008.
[4] Engie n.d. https://www.engie.it/teleriscaldamento.
[5] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, Vad Mathiesen B. 4th Generation District Heating (4GDH) : Integrating smart thermal grids into future sustainable energy systems. 2014.
[6] Dall'O' G, Sarto L, Sanna N, Tonetti V, Ventura M. On the use of an energy certification database to create indicators for energy planning purposes: Application in northern Italy. Energy Policy 2015.
[7] D'Alonzo V, Novelli A, Vaccaro R, Vettorato D, Albatici R, Diamantini C, et al. A bottom-up spatially explicit methodology to estimate the space heating demand of the building stock at regional scale. Energy Build 2020;206:109581. http://dx.doi.org/10.1016/j.enbuild.2019.109581.
[8] Ministero dello sviluppo economico, Ministero dell'ambiente e della tutela del territorio e del mare, Ministero delle infrastrutture e dei trasporti. Piano nazionale integrato per l'energia e il clima. 2019.
[9] Ministero dell'ambiente e della tutela del territorio e del mare, Ministero dello sviluppo economico, Ministero delle infrastrutture e dei trasporti, Ministero delle politiche agricole, Alimentari e forestali. Strategia Italiana di lungo termine sulla riduzione delle emissioni dei gas a effetto serra. 2021.
[10] Paardekooper S, Lund RS, Mathiesen BV, Chang M, Petersen UR, Grundahl L, David A, Dahlbæk J, Kapetanakis IA, Lund H, Bertelsen N, Hansen K, Drysdale DW, Persson U. Heat roadmap Europe quantifying the impact of low-carbon. 2018.
[11] Pezzutto S, Zambotti S, Croce S, Zambelli P, Scaramuzzino C, Pascuas RP, Haas F, Lucchi E, Della Valle N, Eurac AZ, Müller A, Tuw MH, Fleiter T, Klingler A, Kühnbach M, Manz P, Marwitz S, Rehfeldt M, Steinbach J, Popovski E, Kranzl L, Tuw SF. Hotmaps_ D2. 3 WP2 report – Open data set for the. 2019.
[12] Dénarié Fattori, et al. Valutazione del potenziale di diffusione del teleriscaldamento efficiente sul territorio nazionale. 2020, https://www.airu.it/pubblicato-lo-studio-sulle-potenzialita-di-sviluppo-del-teleriscaldamento-in-italia/.
[13] Mathiesen BV, Bertelsen N, Schneider NCA, Garcia LS, Paardekooper S, Thellufsen JZ, Djorup SR. Aalborg Universitet Towards a decarbonised heating and cooling sector in Europe Unlocking the potential of energy efficiency and district energy Paardekooper, Susana; Thellufsen, Jakob Zinck ; Djørup, Søren Roth. 2019.
[14] Rosa D. Experience and potential of low-temperature district heating annex X final report toward 4th generation district heating: Experience and potential of low-temperature district heating Short title: Toward 4th generation district heating. 2014.
[15] Lund R, Persson U. Mapping of potential heat sources for heat pumps for district heating in Denmark. Energy 2016.
[16] Bühler F, Holm FM, Huang B, Andreasen JG, Elmegad B. Mapping of low temperature heat sources in Denmark. In: ECOS 2015-28th int. conf. effic. cost, optim. simul. environ. impact energy syst.. 2015.
[17] Kontu K, Rinne S, Junnila S. Introducing modern heat pumps to existing district heating systems – Global lessons from viable decarbonizing of district heating in Finland. Energy 2019.
[18] Averfalk H, Ingvarsson P, Persson U, Gong M, Werner S. Large heat pumps in Swedish district heating systems. Renew Sustain Energy Rev 2017.
[19] Spirito G, Dénarié A, Fattori F, Macchi S, Motta M, Persson U. Potential diffusion of renewables-based DH assessment through clustering and mapping: a case study in milano. In: 6th international conference on smart energy systems. Aalborg University; 2020.
[20] CENED - Certificazione ENergetica degli EDifici n.d. www.cened.it/dati-cened.
[21] GSE. Valutazione del potenziale nazionale e regionale di applicazione della cogenerazione ad alto rendimento e del teleriscaldamento efficiente. 2016.
[22] Hotmaps Toolbox n.d. https://www.hotmaps.eu/map.
[23] Caputo P, Pasetti G. Boosting the energy renovation rate of the private buildings stock in Italy: Policies and innovative GIS-based tools. Sustainable Cities Soc 2017.
[24] European Commission. Financial support for energy efficiency in buildings. 2013.
[25] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011.
[26] Persson U, Werner S. Effective width: The relative demand for district heating pipes length in city areas. In: 12th int. symp. dist. heat. cool.. 2010.
[27] Werner S, Persson U, Wiechers E, Bernd M. Heat Roadmap Europe: Heat distribution costs. 2019.
[28] Dénarié A, Macchi S, Fattori F, Spirito G, Motta M, Persson U. A validated method to simulate district heating network topologies to enable assessing district heating costs. In: 6th international conference on smart energy systems. Aalborg University; 2020.
[29] Danish Energy Agency – Technology Data. https://ens.dk/en/our-services/projections-and-models/technology-data.
[30] https://www.ecoinvent.org/support/faqs/first-time-users/how-do-i-cite-ecoinvent.html.
[31] https://www.cambridge.org/core/books/climate-change-2013-the-physical-science-basis/BE9453E500DEF3640B383BADDC332C3E.
[32] Famiglietti J, Gervini L, Sprito G, Pozzi M, Dénarié A, Scoccia R, Motta M. Environmental life cycle assessment scenarios for district heating network. An Italian case study. In: International symposium on district heating and cooling. 2021.
[33] CURIT – Catasto impianti termici Lombardia <www.curit.it/opendata>.