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Environmental Life Cycle Assessment scenarios for a district heating network. An Italian case study

Jacopo Famiglietti*, Luisa Gerevini, Giulia Spirito, Marianna Pozzi, Alice Dénarié, Rossano Scoccia, Mario Motta

Department of Energy, Politecnico di Milano, 20156 Milano, Italy

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Abstract

District heating networks have present and future great potential in decarbonization and in general for improving the environmental profile of the European building sector. It is due to the integration of solar-thermal energy and other renewable sources, flexibility by thermal storage, and mainly the ability to recover industrial and municipal waste heat: providing benefits at the element (energy system) and city level. However, individual appliances, such as electric-driven heat pumps, are and will be an attractive option; the decarbonization process of the European electricity grid makes them very appealing from an environmental perspective (from an energy system viewpoint). In this paper, the authors investigate the environmental competitiveness of a district heating network to provide space heating and domestic hot water using the Life Cycle Assessment method. The evaluation was carried out for a new building area (approx. 26 500 m^2 of net surface) located in Milan. The present and future (2030) environmental profiles of North Milan's district heating network were assessed and compared with three individual electric-driven heat pumps (groundwater-source and 450 kW capacity each), as an alternative energy system. 16 potential impact categories were evaluated using, 1 kWh of thermal energy as a functional unit, ecoinvent as background database, and the Environmental Footprint 3.0 as impact assessment method. The results indicated that despite the higher CO_2eq emissions compared to the heat pumps (208 vs 118 gCO_2eq/kWh$_{th}$), district heating could potentially have an almost equivalent climate change impact in the future, due to the integration of renewables sources, feasible with the 4th generation. The value of district heating and electric-driven heat pumps were 89 and 81 gCO_2eq/kWh$_{th}$, respectively for 2030. In contrast, the weighting results showed a better environmental profile for the district heating in both scenarios, allowing a reduction of 67% (in the present) and 19% (in the future).

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Keywords: Life Cycle Assessment; Energy system comparisons; 3rd and 4th district heating; Heat pump

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* Corresponding author.
E-mail address: jacopo.famiglietti@polimi.it (J. Famiglietti).

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Nomenclature

U_{door}	thermal transmittance of doors, W/m^2 K
U_{floor}	thermal transmittance of floors, W/m^2 K
U_{roof}	thermal transmittance of roofs, W/m^2 K
U_{wall}	thermal transmittance of walls, W/m^2 K
$U_{windows}$	thermal transmittance of windows, W/m^2

Subscripts

el	electric
th	thermal

Abbreviations

3DH	Third Generation District Heating
4DH	Fourth Generation District Heating
A	Acidification
CC	Climate Change
CHP	Combined Heat and Power plant
DHC	District Heating and Cooling
DHW	Domestic Hot Water
EF	Eutrophication Freshwater
EFW	Ecotoxicity Freshwater
EM	Eutrophication Marine
EoL	End of Life
ET	Eutrophication Terrestrial
EU	European Union
FU	Functional Unit
GHG	Greenhouse Gas
GWHP	Ground Water Heat Pump
HP	Heat Pump
HTC	Human Toxicity Cancer
HTNC	Human Toxicity Non-Cancer
IHR	Industrial Heat Recovery
IR	Ionizing Radiation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impacts Assessment
LU	Land Use
PM	Particulate Matter
PNIEC	Integrated National Energy Climate Plan
POF	Photochemical Ozone Formation
RES	Renewable Energy Sources
RUF	Resource Use, Fossils
RUMM	Resource Use, Mineral and Metals
SCOP	Seasonal Coefficient of Performance
SH	Space Heating
STA	Solar Thermal Array
WTE	Waste to energy
WU	Water Use

1. Introduction

The European Commission set aspiring targets to reduce Greenhouse Gas (GHG) emissions and environmental degradation, as a part of the European Green Deal. By 2030 at least 55% of GHG emissions should be cut, compared to 1990, and to be climate-neutral by 2050 [1,2]. This path should be implemented avoiding significant harm to any other environmental objectives (i.e., climate change adaptation, sustainable use and protection of water resources, transition to a circular economy, pollution prevention and control, protection and restoration of biodiversity and ecosystems) [3]. As is well known, the building sector is responsible for 30%–40% of the total energy consumption in the European Union [4,5] and thus a priority. The European Union (EU) strategic long-term vision indicates among the main energy transition pathways of the heating sector, the electrification of heat and District Heating (DH) networks [6]. The benefits of heat electrification could be summarized in, a clean energy carrier, high developed transmission infrastructure compared with liquid fuels, a very efficient and affordable technology (i.e., heat pumps), etc. The DH is crucial for achieving the climate ambitious targets, thanks to the ability of industrial and municipal waste heat recovery, flexibility by thermal storage, and integration of renewable sources.

Energy systems are commonly compared considering primary energy consumptions, costs, and direct CO_2eq emissions (emitted during the operational phase). Although, an accurate picture of potential impacts besides GHG emissions and the operational phase would be more complete. Thus, the Environmental Life Cycle Assessment (LCA) method [7,8] is increasingly required and used for energy system comparisons.

Previous LCA works were already implemented on the electrification of the heat and DH networks, analyzing their environmental profiles. Summarizing, (i) comparisons [9,10]; (ii) infrastructure evaluations [11–14]; (iii) case studies and feasibilities [15–26]; (iv) reviews [19,27–29]. These studies highlighted the most suitable technologies in terms of potential environmental impact mitigations, energy, and economic savings. In particular, Nitkiewicz and Sekret [24] compared three different heating plant systems (electric groundwater-source heat pump, absorption gas-driven heat pump, and natural gas boiler) as supplying low-temperature DH networks. Bartolozzi et al. [9] compared two types of DH and Cooling (DHC) networks supplied and not by Renewable Energy Sources (RES) with individual appliances. Feofilovs et al. [16] showed the improvement of the environmental profile towards the transition of a conventional 3rd generation (3G) to a 4th generation (4G) DH network.

Similarly, in this paper, the authors investigated the environmental competitiveness of DH and big sizes (three of 450 kW each with thermal storage) individual vapor compression heat pumps (groundwater-source), for now on also referred as “heat pumps”, to provide space heating and domestic hot water for new construction buildings located in the North side of Milan (approx. 25 600 m^2 of net surface), giving present and future (2030) scenarios.

To the best of the authors’ knowledge, only Ristimäki et al. [10] investigated the potential environmental benefits of a DH network in comparison with a ground source heat pump. Unlike the work was focused only on climate change and costs, other environmental impact categories were not assessed.

In this paper, the comparison between the Northern DH network of the city and heat pumps was implement considering the two energy systems as alternative and interesting options for new construction buildings, with floor heating as emission system (low-temperature supply, equal to 60 °C to the end-user). The evaluation was implemented in a present and future scenario allowing the assessment of benefits achievable by, (i) the potential transition from the actual 3GDH to a 4GDH (realized using real design data), and (ii) the Italian National target concerned the decarbonization of the electricity grid devised in the Integrated National Energy Climate Plan (PNIEC) [30] for both (DH and heat pumps). The assessment was carried out applying the LCA methodology and using 16 potential impact categories provided by Joint Research Centre — European Commission, with the Environmental Footprint 3.0 method [31].

2. Methodology

In this section, the authors explained the methodology adopted (attributional LCA) for the comparison of the two energy systems, underlying the system boundaries, the approach to deal with multifunctionalities and cut-off rules, the functional unit, and the Life Cycle Impacts Assessment (LCIA) method. For the evaluation, specific scripts in Python 3.7 were implemented.

2.1. System boundaries

The energy systems were evaluated with a cradle to grave approach, assessing the life cycle phases reported in Table 1 for each kind of system. I.e., Heat Pumps (HPs), Boilers, Combined Heat and Power (CHP) plant, Waste To Energy plant (WTE), and District Heating (DH) network.

Table 1. Life cycle phases assessed per energy system.

Item	HPs and Boilers	CHP and WTE	DH network[a]
Lifespan	20 years	100 000 operational hours	50 years (steel pipes – 3GDH) 35 years (plastic pipes – 4GDH)
Phases	• Component productions (raw material, supply, production). • Assembling (manufacturing with energy and water consumptions, welding, waste, transport of components). • Distribution. • Use stage (energy vector consumptions plus maintenance). • End of life stage (transport, waste processing for reuse, recovery or/and recycling, and disposal).	• Component productions (raw material supply and production). • Transportation from the producer to the installation site. • Planning, installation work, and functional check. • Use stage (energy vector consumptions plus maintenance). • End of life stage (transport, waste processing for reuse, recovery or/and recycling, and disposal).	• Component productions (raw material supply and production). • Transportation from the producer to the installation site. • Installation work (energy vector consumptions). • End of life stage (concrete filled into the pipes).

[a] Excluding the amount of water inside pipes.

2.2. Multifunctionalities and cut-off rules

The authors chose three different approaches to deal with multifunctionalities. (i) System expansion (substitution) was used to evaluate the environmental profile of heat produced by CHPs and WTE. (ii) Allocation based on mass was used for the manufacturing phase and on recycled content (or cut-off) proposed by ecoinvent 3.6 database for the end-of-life modeling [32]. (iii) The environmental profile of heat from Industrial Heat Recovery (IHR) was set equal to zero, in line with the EN 15316-4-5 [33].

In particular the alternative productions used for substitutions (i) [34] were:

- the environmental profile of the electricity (high and medium voltage) delivered by the Italian grid (for turbosteam, reciprocating internal combustion engine, and turbogas CHPs);
- the environmental profile of the electricity (medium voltage) delivered by the Italian grid, and the environmental profile of the solid waste (98% municipal and 2% sludge) treated in sanitary landfill, for WTE. According to the Italian municipal wastes report of 2020 [35], 21% of municipal wastes was disposed in landfill in Italy (the value rises to 95% considering only landfill and incineration without energy recovery scenarios — waste hierarchy, excluding the most favorable disposal options before WTE as per regulations, i.e. reuse, recycling, and composting). The avoided burden of municipal wastes disposed in sanitary landfill was implemented considering that the 28% of biogas produced was recovered, equal to 0.065 Nm^3 of natural gas avoided per kg of waste [36]. Landfill disposal in the next 15 years will be halved (not eliminated) so this alternative production was considered for 2030 as well.

System expansion was utilized not only because it was imposed as the first hierarchical choice by the standards (ISO 14040–44), but also to highlight the benefits that DH brings to the city — the ability to recover industrial and municipal waste heat.

The cut-off rule was set at 1% in terms of environmental impacts [37], meaning that inputs and outputs below this threshold were not included in the evaluation. E.g., packaging materials and their transports.

2.3. Functional unit

The Functional Unit (FU) was set as 1 kWh of thermal energy provided to the end-user by the DH and heat pumps for services of space heating and domestic hot water. The net surface of the buildings was established equal to 25 600 m^2 (with specific geometric characteristics and thermophysical performances), located in Milan.

2.4. Life cycle impacts assessment

The environmental profile of DH and heat pumps was expressed considering 16 impact categories, following the EF method 3.0 normalization and weighting set — impact assessment method of the Environmental Footprint initiative [31]: (1) Climate Change with a time horizon of 100 years (CC); (2) Ozone Depletion with a time horizon of 100 years (OD); (3) Ionizing Radiation (IR); (4) Photochemical Ozone Formation (POF); (5) Particulate Matter (PM); (6) Human Toxicity Non-Cancer (HTNC); (7) Human Toxicity Cancer (HTC); (8) Acidification terrestrial and freshwater (A); (9) Eutrophication Freshwater (EF); (10) Eutrophication Marine (EM); (11) Eutrophication Terrestrial (ET); (12) Ecotoxicity Freshwater (EFW); (13) Land Use (LU); (14) Water Use (WU); (15) Resource Use, Fossil (RUF); (16) Resource Use, Mineral and Metals (RUMM).

3. Life cycle inventory analysis

In this section, the Life Cycle Inventory (LCI) of the appliances was explained, considering the system boundaries already provided.

As described, the buildings of 26 500 m^2 of net surface are new buildings that will be built in the Northern area of Milan, in the following 5 years. The intended use of the constructions can be summarized as follows, 66% of social housing, 25% of student residence, 3% of offices, and 6% of commercial area. A specific model in Trnsys software [38] was implemented considering the U-values reported in Table 2. The total amount of energy needs was equal to 1 118.3 MWh_{th} / year, considering a specific demand (in m^2) of 23.5 kWh_{th}/m^2 year for Space Heating (SH) and 18.7 kWh_{th}/m^2 year for Domestic Hot Water (DHW).

Table 2. U value for the buildings analyzed.

Item	U [W/m^2 K]
Uwall	0.11
Uroof	0.15
Uwindows	1.30
Udoor	1.30

3.1. District heating network

The LCIs for the DH network were implemented using data provided by manufacturers and data available in the literature. In particular:

- the number of appliances, the efficiencies, and the energy supplied from the 3GDH (Northern Milan) was assessed by consulting reports of the Italian Association of the Urban Heating [39] and primary data provided by A2 A S.p.A. (the main operator of DH networks in Milan and the sole concessionaire for the distribution of district heating service on the city's public land);
- the capacity and the energy supplied for each energy system of the 4GDH were assessed by implementing a specific model in energyPRO version 4.5 [40]. The efficiencies were declared by manufacturers;
- the components and lifespan of each appliance were evaluated through reports provided by the ecoinvent database and the "Space and combination heaters — Ecodesign and Energy Labeling" report — European Commission [41];
- as stated, the heat pump was also evaluated using ecoinvent data, including the borehole construction. The length of the borehole was set equal to 150 m, the deeper depth of the water table in Milan (conservative approach), with a diesel consumption for drilling equal to 465 liters (3.1 liters/m), and water consumption

Table 3. 3GDH (North side of Milan) scenario – present[a].

Item	# of appliances	Electrical and thermal power [MW]	Seasonal electrical and thermal efficiency [%]	3GDH [GWh_{th}/y]	3GDH [%]
Boiler 1	3	25	88.8	8.4	2.4%
Boiler 2	5	91.6	88.8	64.3	18.5%
Boiler 3	4	10	88.8	20.1	5.8%
CHP 1 (reciprocating internal combustion engine)	3	9.6 and 9.0	43.4 and 37.0	6.8	1.9%
CHP 2 (turbogas plus turbosteam)	1	53.2 and 60.5	33.2 and 32.1	94.9	27.2%
CHP 3 (turbogas plus turbosteam)	1	57.3 and 30.6	33.2 and 32.1	48.0	13.8%
CHP 4 (turbogas)	2	10.0 and 16.0	43.4 and 37.0	12.0	3.4%
Waste to Energy	1	5.5 and 13.0	20.7 and 27.2	73.9	21.2%
Industrial heat recovery	1	3.0	–	20.0	5.7%
Total	–	–	–	348.3	100.0%

[a] The heat losses were set equal to 12% (41.8 GWh_{th}/year).

of 10.2 m^3. Construction materials were also evaluated (i.e., steel, cement, bentonite, and polyethylene). Concerning the withdrawal water (from ground source), 100% of it was considered discharged into a surface body — for environmental constraints linked to the temperature, the released water shall not be reintroduced into the aquifer. Although the withdrawal generates a change in the hydrological cycle, the impact on the water resource was not assessed. The EF 3.0 (that uses AWARE — Relative Available WAter REmaing method) simplifies by not characterizing groundwater and surface water with different factors (in absolute terms). The pumping consumptions were considered in the SCOP, equal to 10% of the electricity demand. The leakages of gas, instead, were obtained by "Impacts of leakage from refrigerants in heat pumps" report [42] and set equal to 4% per year;

- the data of construction materials used for the network were obtained consulting Fröling et al. [11] for the 3GDH (steel pipes, total length 356 km, lifespan 50 years) and Bartolozzi et al. [9] for the 4GDH (plastic pipes, total length 2 km, lifespan 35 years);
- the electricity used to power the systems was evaluated referring to the current national mix for the present scenario (ecoinvent 3.6) and considering the targets devised in PNIEC [30] for the future scenario. The CO_2eq factors utilized were 419 gCO_2eq/kWh_{el} vs 226 gCO_2eq/kWh_{el} for low voltage and 447 gCO_2eq/kWh_{el} vs 308 gCO_2eq/kWh_{el} for medium voltage (basing the calculation on Gargiulo's article data);
- the energy demand for pumping the water within the network was considered equal to 0.5% of the energy provided to the final consumer [43];
- the energy losses in the network were set equal to 12% for 3GDH [39] and equal to 10% for 4GDH [43].

Tables 3 and 4 show the DH networks analyzed. The columns "3GDH" and "4GDH" report the amount of energy produced by each energy system that supplies the networks. The share of renewable energy sources for 4GDH was equal to 69%.

3.2. Heat pumps

As for the DH network, the LCI of the three heat pumps chosen as an alternative energy system was assessed using data provided by manufacturers and data from literature. In summary:

- the capacity and the Seasonal Coefficient Of Performance (SCOP) were assessed, as already stated, by a specific energy model in Trnsys software. According to the result obtained, three different individual heat pumps of 450 kW each with thermal storage of 5 000 liters were chosen concerning the geometry of the area (building positions). The SCOPs were set equal to 4.0 (pumping included);
- the components and lifespan of each appliance were evaluated as described in the section related to the DH. Also in this case, the gas used was the R134a.

Table 4. 4GDH scenario — future[a].

Item	# of appliances or surface	Producibility or power	Seasonal efficiency and SCOP (pumping included)	4GDH [MWh_{th}/y]	4GDH [%]
Solar thermal array with thermal storage of 100 m^3	500 m^2	925.2 kWh/m^2 year	–	462.6	37.2%
Groundwater heat pump (gas R134a)	# 1	300 kW	4.0	521.8	42.0%
3GDH as a backup	See Table 2	See Table 2	The thermal and electrical efficiencies of CHP 2 and CHP3 were increased to 43.4 and 37.0. For the other energy systems see Table 2.	260.2	20.8%
Total	–	–	–	1 244.6	100.0%

[a] The heat losses were set equal to 10% (126.3 MWh_{th}/year).

4. Results and discussion

In this section the results obtained by transforming the LCIs explained previously in potential environmental impacts, are shown.

Table 5 reports the characterization results for each impact category outlined in the EF method 3.0 [31]. The outcomes are presented in relation to 1 kWh_{th} provided to the final consumer (FU selected for the analysis). Negative values, shown in the table, are the consequence of using the system expansion (substitution) as approach to deal with multifunctionalities.

The two columns “Difference” and “Ratio” were inserted to better understand the results achieved. The values presented in the “Difference” column were calculated as a difference between DH and Heat pumps, while the values in the “Ratio” column are the ratio of “Difference” and “Heat pumps” values.

In Fig. 1, climate change impact is plotted against the weighting results. With the weighting (optional step in LCA), the characterization results of different impact categories (showed in Table 5) were converted by using numerical factors that express the relative importance of each category. To obtain the weighting results, the characterized values were firstly normalized, thus divided by selected reference, and then converted by using numerical factors based on value-choices. In this article, the authors used, as already stated, the EF 3.0 method that utilizes, (i) the global annual released mass of each impact category per person (considering a world population equal to 6 895 889 018) to calculate the normalization factors and (ii) a panel-based method for weighting, giving the higher factor to climate change and the lower to human toxicity non-cancer [44].

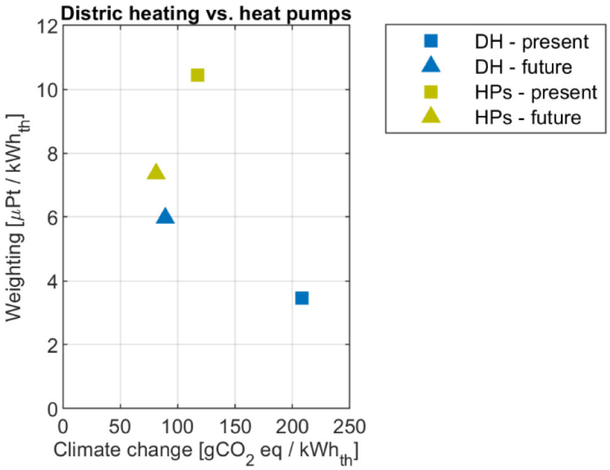

Fig. 1. Comparison between DH and heat pumps (present and future scenario).

Table 5. Characterization results for FU.

Potential impacts	Scenario[a]	Units	DH	Heat pumps	Difference	Ratio [%]
Climate change	Present	kg CO_2 equivalent (CO_2 - Carbon dioxide)	2.08E−01	1.18E−01	9.07E−02	+77%
	Future (2030)		8.92E−02	8.12E−02	7.98E−03	+10%
Ozone depletion	Present	kg CFC-11 equivalent (CFC-11 – Trichlorofluoromethane)	4.16E−08	2.26E−08	1.90E−08	+84%
	Future (2030)		1.57E−08	2.21E−08	−6.45E−09	−29%
Ionizing radiation	Present	kBq U_{235} equivalent	−3.97E−02	5.91E−03	−4.56E−02	−772%
	Future (2030)		−8.29E−03	4.78E−03	−1.31E−02	−273%
Photochemical ozone formation	Present	kg NMVOC equivalent (NMVOC - Non-methane volatile organic compounds)	−7.09E−05	2.68E−04	−3.39E−04	−126%
	Future (2030)		1.22E−04	1.58E−04	−3.63E−05	−23%
Particulate matter	Present	disease incidence	−3.20E−09	6.19E−09	−9.39E−09	−152%
	Future (2030)		6.23E−10	2.15E−09	−1.52E−09	−71%
Human toxicity, non-cancer	Present	Comparative Toxic Unit for humans (CTUh)	4.72E−10	9.40E−10	−4.68E−10	−50%
	Future (2030)		1.32E−09	8.99E−10	4.23E−10	+47%
Human toxicity, cancer	Present	Comparative Toxic Unit for humans (CTUh)	2.58E−11	4.50E−11	−1.92E−11	−43%
	Future (2030)		4.45E−11	3.42E−11	1.03E−11	+30%
Acidification	Present	mol H+ equivalent (H+ Hydron)	−1.02E−03	1.16E−03	−2.18E−03	−188%
	Future (2030)		1.36E−04	3.67E−04	−2.31E−04	−63%
Eutrophication freshwater	Present	kg P equivalent (P – Phosphorus)	−3.08E+00	6.15E−06	−3.08E+00	−50E+6
	Future (2030)		4.77E−06	1.93E−06	2.84E−06	+148%
Eutrophication marine	Present	kg N equivalent (N – Nitrogen)	−6.14E−04	9.71E−05	−7.12E−04	−733%
	Future (2030)		−8.20E−05	4.50E−05	−1.27E−04	−282%
Eutrophication terrestrial	Present	mol N equivalent (N – Nitrogen)	−1.10E−03	3.53E−03	−4.63E−03	−131%
	Future (2030)		3.17E−04	7.17E−04	−4.00E−04	−56%
Ecotoxicity freshwater	Present	Comparative Toxic Unit for ecosystems (CTUe)	−3.08E+00	1.43E+00	−4.51E+00	−315%
	Future (2030)		6.78E−01	9.92E−01	−3.14E−01	−32%
Land use	Present	Soil Quality Index (Pt)	−1.18E+00	6.04E−01	−1.78E+00	−295%
	Future (2030)		1.39E−01	7.53E−01	−6.14E−01	−82%
Water use	Present	m^3 deprived	−1.45E−01	7.81E−02	−2.23E−01	−286%
	Future (2030)		−7.04E−03	6.51E−02	−7.21E−02	−111%
Resource use, fossils	Present	MJ	4.03E+00	1.60E+00	2.43E+00	+152%
	Future (2030)		1.42E+00	1.16E+00	2.58E−01	+22%
Resource use, mineral and metals	Present	kg Sb equivalent (Sb - Antimony)	−1.01E−07	2.51E−07	−3.52E−07	−140%
	Future (2030)		9.06E−07	1.17E−06	−2.64E−07	−23%

[a] Present: 3GDH and heat pumps powered by the current national electricity mix. Future: 4GDH and heat pumps powered by the national electricity mix foreseen for 2030 in Italy.

The Figure shows the decarbonization (climate change) of the two energy systems analyzed and emphasizes, with weighting, the whole environmental profile. The burden-shifting of the DH from the present to the future scenario (a decrease of climate change vs an increase of weighting) is due to the electrification of the heat with the groundwater source heat pump (42.0% of share), and the lower benefit from the substitution approach in CHPs produced by the better environmental profile of the electricity in 2030.

Today and in the next future (2030) the electrification of the heat, using the Italian electricity mix, causes a worsening of the environmental profile (compared to natural gas) concerning several impact categories (as shown in Fig. 2 — weighting results per impact category), such as (i) Ionizing Radiation (IR) and toxic categories (HTNC, HTC, and EFW) due to the import of electricity from nuclear plants from France; (ii) Water Use (WU) because of electricity produced by hydropower plants; (iii) Acidification (A) and eutrophication categories (EF, EM, and

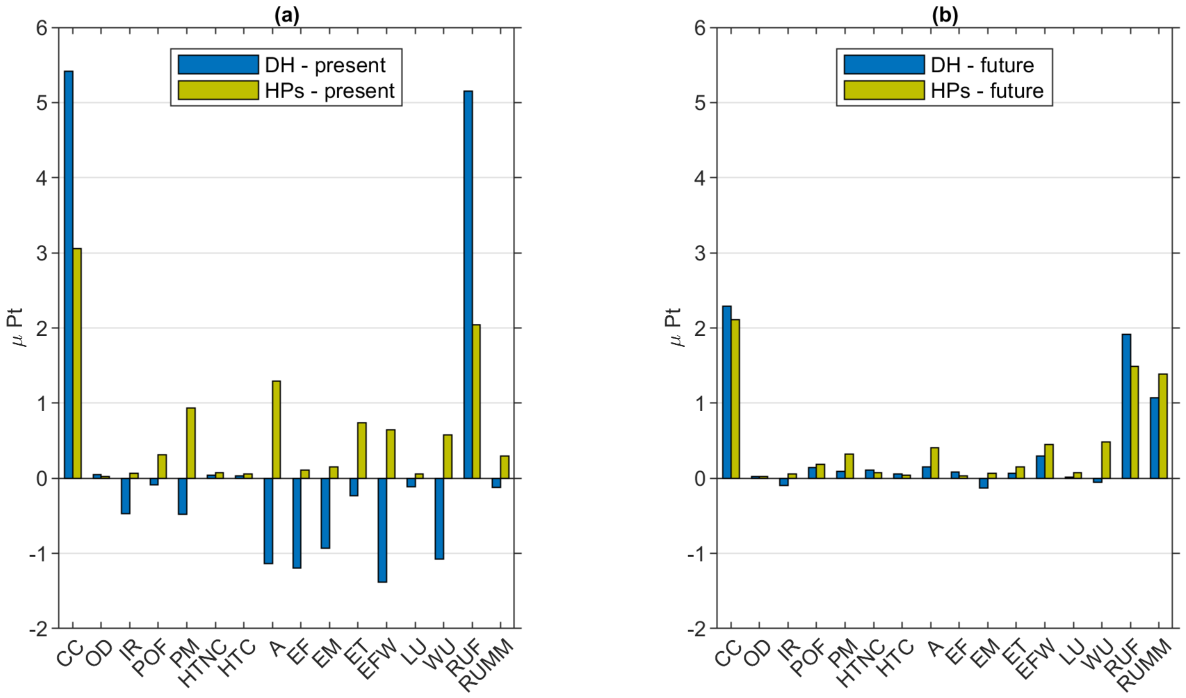

Fig. 2. Weighting results per impact category, present scenario (a) and future scenario (b).

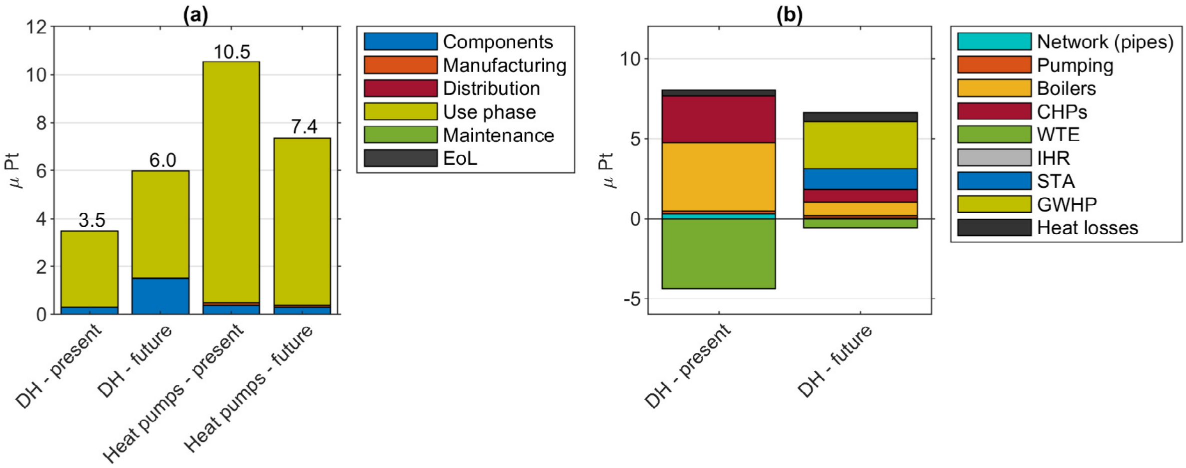

Fig. 3. (a) Weighting results in μPt/kWh$_{th}$. (b) Contributions to weighting results for DH scenarios μPt/kWh$_{th}$.

ET) caused by electricity production from oil fuel plants; (iv) Resource Use, Mineral and Metals (RUMM) due to electricity production from photovoltaic plants.

Fig. 3 shows the contribution to the weighting results by presenting the DH's environmental profile for each life cycle stage and element (central heating plants, network, etc.). As reported, a significant benefit is provided by WTE. This benefit is reduced by moving from the present to the future scenario caused by, a decrease in heat supply from 21% to 5% and a lower benefit from avoided electricity production, as outlined before.

Based on the data collected and the assumptions taken, the use phase had the most significant impacts, contributing 92% for "DH — present", 75% for "DH — future", 95% for "Heat pumps — present", and 95%

for “Heat pumps — future”. The component production is the second important stage, contributing approx. 9% for the “DH — present”, 25% for the “DH — future” scenario, and 4% for heat pumps. The high impact of the components’ production stage for the “DH — future” is due to the Solar Thermal Array (STA). The order of magnitude of these findings (results and the contribution of different stages) were in line with those shown by previous authors [9,37,45].

5. Conclusions

In this paper, the Northern district heating network of the city of Milan was compared, through attributional Life Cycle Assessment approach, with vapor compression heat pumps (groundwater source) as alternative solutions to provide space heating and domestic hot water for new building constructions. The comparison was implemented considering a present and future scenario (2030) taking into account the potential transition, (i) from the actual 3rd generation to a 4th generation district heating network and (ii) from the actual to the future Italian electricity grid devised in the Integrated National Energy Climate Plan. All relevant processes and stages were considered in the analysis.

The results indicate that despite the current higher CO_2eq emissions compared to the heat pumps (208 vs 118 gCO_2eq/kWh_{th}), district heating could potentially have an almost equivalent climate change impact in the future, due to the integration of renewables sources, feasible with the 4th generation. The value of district heating and vapor compression heat pumps were 89 and 81 gCO_2eq/kWh_{th}, respectively, for the 2030 scenario. In contrast, the weighting results indicate a better environmental profile for the district heating network in both scenarios, allowing a reduction of 67% (in the present) and 19% (in the future) compared with the heat pumps. In conclusion, the results show that district heating has a potential that makes it environmentally competitive. In this pathway, the improvement of the existing 3rd generation (used in this study as a backup for the future scenario) is a mandatory step to be implemented, with the integration of heat recovery and increased efficiency of existing appliances, as suggested by Pozzi et al. [46]. The path shall occur limiting (or better avoiding) the environmental burden-shifting, reported in Fig. 1.

With this study the authors highlight how LCA analysis allows to evaluate the potential impact of the systems by considering more impact categories at the same time, thus providing an overall view. The starting point for future enhancements of this article is to improve the quality of the primary data collected. In particular, more detailed data of sanitary landfill should be used to assess a high reliable environmental profile of the avoided burden from solid waste disposed of, used in the waste to energy plant model. Besides, local scenarios should be considered for the application of the substitution method, currently assessed using average Italian data (for avoided production of electricity and waste disposed of). The water consumption of heat pumps to produce heat should be evaluated more accurately, avoiding the simplification made in considering the water released in the surface body with the same characterization factor (in absolute value) of the water taken from the ground. Moreover, the consistency of the results should be tested through uncertainties (Monte Carlo) and sensitivity analysis, concerning the method used for the impact assessment and the background processes (from ecoinvent) chosen.

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.

Appendix A. Supplementary data

Supplementary material related to this article containing three MS Excel files: (i) the normalization results, (ii) the Italian Electricity mix at 2030, and (iii) the model implemented for the WTE can be found online at https://doi.org/10.1016/j.egyr.2021.08.094

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