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Economic comparison of heating and cooling supply systems in warm climates – using a case study

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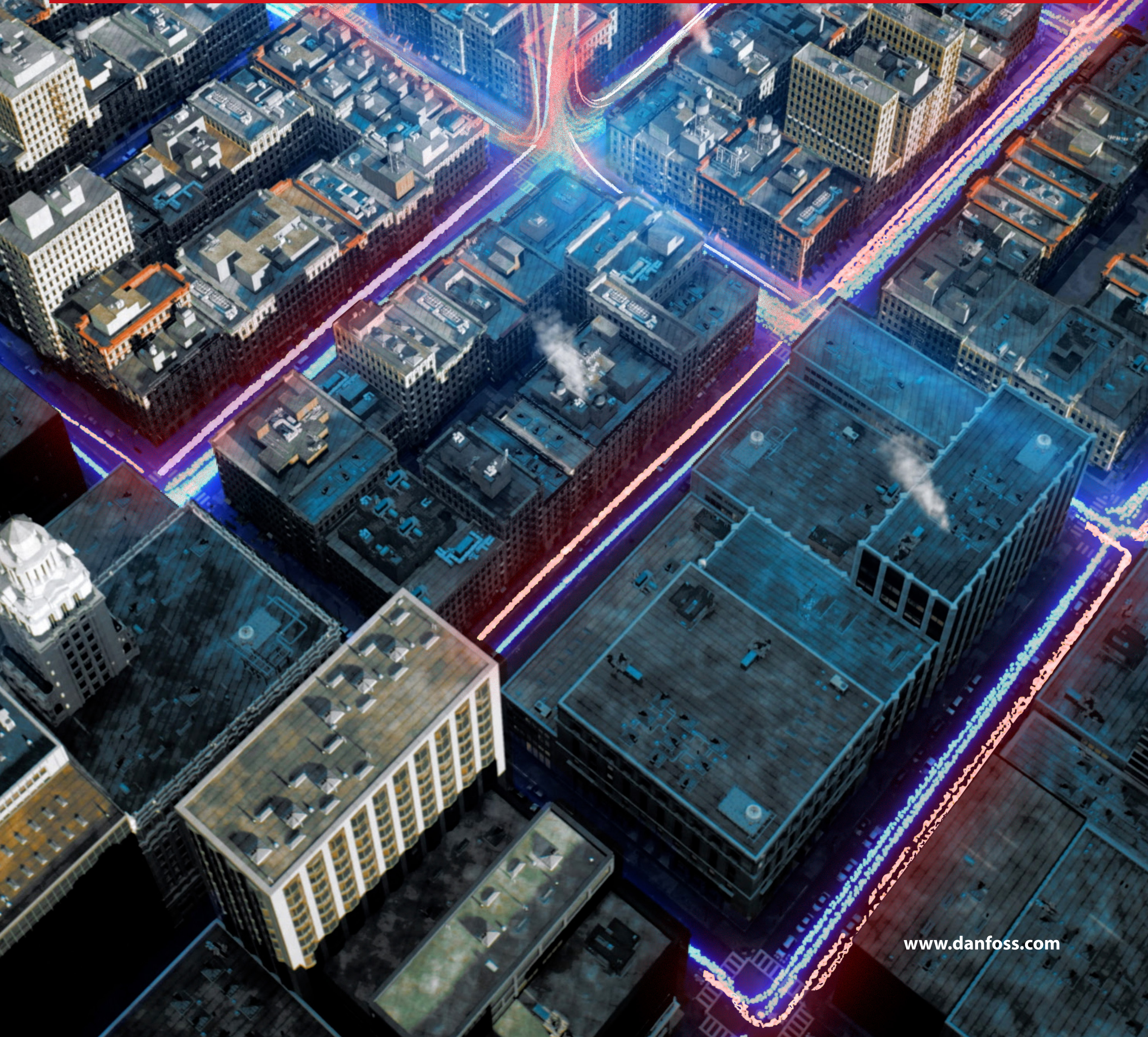

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Abstract

District energy systems are widely recognized as a sustainable and future proof solution for fulfilling urban heating demands in cold climates. However, the question remains on their applicability in climates requiring both heating and cooling of buildings. While district energy systems are traditionally designed for fulfilling either heating or cooling demands the latest system designs offer the possibility for integrating both heating and cooling demands into the same system. The commonality with these systems is low operating temperatures, which offers the possibility for end-user to use the network as a heat source, or heat sink, for their own heat pumps. These end-users are commonly referred to as prosumers, as they can both take, and delivery, thermal energy at useful temperature levels to the district energy system. This paper compares the levelized cost of heating and cooling for fulfilling space heating, space cooling and domestic hot water demands of a neighborhood with a mixture of new and old buildings in Rome, Italy, when applying low temperature district heating (4GDHC), ultra-low temperature district heating (5GDHC) and building level heating and cooling solutions. The results indicate that 4GDHC is the most competitive heating and cooling supply solution for the considered case.

1. Introduction

District energy (DE) is a terminology for centrally based thermal systems. DE includes two concepts, district heating (DH), which covers centrally generated heat supply for fulfilling heating demands of its connected users, and district cooling (DC) which opposite to DH is a system for removing heat from the connected users and discarding it at a suitable central location. Both DH and DC have roots back to the 1880s and have had, based on its major developments, been classified in generations.

The historical development of DH, from a high temperature steam system, 1st generation DH, to a low temperature and multi heat source system, 4th generation DH, is described in [1]. In [2] an ultra-low temperature district heating and cooling system was defined, commonly referred to as the 5th generation district heating and cooling (5GDHC). The defining feature of 5GDHC is the requirement of building level heat pumps for boosting the system supply temperature to a temperature level necessary for fulfilling either the heating or cooling demands of the end-users. In other words, the fundamental difference is the transition from using directly useful temperature levels for fulfilling the end-user thermal demands towards being a thermal source and sink service for building level heat pumps. Due to the active thermal exchange with the network the end-users can in principle help with maintaining the thermal balance of the distribution network, hence the end-users are often argued to be prosumers [3], [4]. This however require a loose definition of the term prosumers, which generally refers to an end-user operating his own energy plant for fulfilling his own energy needs and delivers excess energy production to the energy grid [5]. In the 5GDHC system the end-users deliver their non-useful waste streams into the grid, e.g. they are not actively generating thermal energy for the system. In [6] and [7] it is argued that the 5GDHC is not compatible with the original definition of the generations of DH, due to its individual thermal generation nature, but should be considered a promising technology with its own merits.

The historical development of district cooling is described in [8], where the 1st generation is an industrial refrigeration system, followed by the 2nd generation which changes the distribution medium to water and applies economy of scale, the 3rd generation which is defined by diversification of cooling sources and the 4th generation which positions DC within the smart energy system. Unlike DH systems DC systems are generally built for serving large buildings with cooling demand all year, such as office buildings, malls and buildings which in addition to cooling loads due to climate condition have cooling demands due to internal heat gains, such as ventilation, humidity control and operation of electronic equipment.

With the transition from fossil fuels district heating (DH) is well positioned for becoming the lead heat supply system for urban areas in heat demand dominated regions. The question however remains how well-suited DH is compared to individual heat pumps for replacing natural gas-based heating in regions with both heating and cooling demands. The benefit with individual heat pumps in warm climates is the near one-to-one replacement of existing gas boilers and the simple change of the drive energy supply from the gas grid to the power grid. Further, the heat pump will give the ability to fulfill domestic hot water (DHW), space heating and cooling demands using the same unit. This individual electrification of the heating demand may although pose challenges to the power grid, namely require potential grid strength enhancements and large renewable power generation capacity, that will stand idle during large parts of the year due to seasonality of building thermal demands.

Replacing the natural gas-based supply system with district energy (DE) will on the other hand require new infrastructure, a water-based pipe network connecting all buildings in an area with one or more thermal plants. Compared to individual thermal supply systems DE has couple of advantages, a) building heat interface units are simple, b) economy of scale from supplying the aggregated demand from few large thermal generation plants, c) ability to switch between a wide range of energy vectors based on availability or cost, and d) the ability to use thermal energy storages to decouple thermal demands and generation for extended periods.

The economic competitiveness of small-scale DH system to individual heat supply solutions has been evaluated for Denmark in [9] and the results shows DH to have a robust cost advantage to other heat supply system, both in relation to area heat density and energy ratings of the connected buildings. The economics of 4GDH and 5GDH was compared for heating dominated areas in [7] and showed that in such situation the 4GDH is more cost efficient for both existing and new low energy buildings. The question however remains which solution is better suited in areas where there is a mix of both heating and cooling demands.

The purpose of this paper is to present the results of a techno-economic comparison analysis between 4th and 5th generation systems for residential areas that have both heating and cooling demands. The analysis is performed for a new area in Rome, Italy, covering a mixture of single and multi-apartment buildings, which are further a mix of existing and new standard buildings, as defined by [10].

For the 4th generation two variants are considered, a) a combination of a 4GDH system for heating demands and individual solutions for cooling demands, and b) a 4GDH and cooling (4GDHC), where the end-user have a heat pump module integrated into the heat interface units for fulfilling the cooling demands and use the DH network as a heat sink for the waste heat from the cooling operation. For the 5GDH and cooling (5GDHC) system the building level heat pumps use the DHC grid both as a heat source and a heat sink for fulfilling the heating and cooling demands of the buildings. For both the 4GHDC and 5GHDC system a DHW thermal storage is considered for maximizing own consumption of waste heat from the cooling operation.

1.1 State-of-the-art review on **the economic performance of 5GDH networks**

The economic performance of 4GDH networks has been demonstrated several times [11], [12]. An analyses of the benefits of low(er) system temperatures is presented in [13] and the modernization of 2nd and 3rd generation systems towards 4GDH are presented in [14], [15]. The latest conceptual development in the district energy sector is to move the thermal generation to building level heat pumps, which significantly reduces network temperature requirements, these systems are often called 5GDHC systems. However, there are only a few 5GDH networks realized so far and they are typically small scale [2]. Currently there are few studies available that are comparing 5GDHC with 4GDH and 4GDHC system in a systematic manner.

According to [3] the technical or economic feasibility of 5GDHC networks for larger applications is unclear, that statement is supported by an Austrian 5GDH network studies [16], [17], which point out, that the analyses of the economic feasibility for 5DGH networks is challenging, since there is very little practical experience available. In general, the investment costs are very high and the required rate of return has a great influence on the heat production costs. The authors identify that economy of scale as well as modular, standardized components are projected to be important factors for further 5GDHC deployment. A similar conclusion is achieved in [2], where it is concluded that the investment cost is the main barrier for developing a sustainable 5GDH system. In [18], the economic parameters of different 5GDH configurations are compared against gas boilers, electric chillers, and grid electricity in a UK context.

A commonality of the above 5G papers is that they focus on the system structure and compare it to individual based heating and cooling systems, they do not compare 5G against the 4G.

An intermediate step between 4GDH and 5GDH is a DH network that has sufficient supply temperature for space heating but requires temperature boosting for DHW needs at the end-users side – often called Ultra-Low Temperature DH (ULTDH). Example of research can be found in [19], which focuses on different boosting methods, [20] which focused on the economic benefits of ULTDH compared to 4GDH, [21] looked into the system efficiency improvement potentials of ULTDH compared to 4GDH and showed that it matters if the main heat supply is coming from a central heat pump or a CHP, and [22] looked into the total energy system costs of various DH systems in Danish context and identified 4GDH being the most cost efficient thermal supply system. While ULTDH can have positive improvements on the system efficiency compared to 4GDH they generally need special conditions to be more cost efficient.

In terms of heat pump operation, [23] is pointing out that centralized and larger scale HPs in 4GDH networks can more easily participate on electricity markets, due to more cost-effective thermal storages, larger capacities, larger energy volumes and they are more likely to get prequalified. The benefits of decentralized HPs is that they can increase self-consumption of locally generated electricity (e.g. rooftop PV).

1.2 Research question: A quantitative comparison of **4GDH individual cooling, 4GDHC, 5GDHC** and **individual heat pumps**

While the combination of economics of scale achieved by district heating systems supplying dense urban areas, the ability to take advantage of low-cost local heat sources and short-term variations in cost of energy vectors, makes them attractive in cold climates the question is open how economic district heating networks are in mild climates, with both heating and cooling demands.

In [24] it was concluded, that both 4GDH and 5GDH share to some extent the five essential abilities of modern DH systems:

1. Heat supply to existing, renovated, and new buildings.
2. Have low grid losses.
3. Use low-temperature waste heat / renewable heat sources.
4. Are an integrated part of smart energy systems.
5. Ensure suitable planning, cost and incentive structures.

However, the specific configurations between these system types are very different and therefore the cost structure becomes different. This paper is filling this gab by directly comparing the levelized cost of heating and cooling (LCOHC) for different network configurations. The comparison is considering the complete energy transformation chain from source to sink.

While the general setup of the central heat plants for DH system are generally dependent on the local conditions and system design, particularly the designed operating temperatures, this analysis takes a simplified approach and assumes that both the 4th and 5th generation DH systems rely on the same heat and cool generation units.

In the analysis 4 district heating system variants are compared to each other, as well as to building level air source heat pumps. The considered variants are as follows:

- **4GDHC:** In this variant a building/flat level heat pump is integrated into the standard district heating substation. The supply temperature from the DH system is sufficient for direct fulfillment of both space heating and DHW demands. The integrated heat pump is used for fulfilling the end-user cooling demands. The waste heat from the cooling operation is prioritized for fulfilling own DHW demands, via DHW storage tank. Any excess waste heat from the cooling operation is delivered into the 4GDHC network at the system supply temperature.
- **4GDH in combination with individual cooling:** This variant represents the standard 4GDH system operation, which has a supply temperature sufficient for direct fulfillment of both space heating and DHW demands. The cooling demand is addressed by individual air source heat pumps units at each end-user.
- **High temperature 5GDHC (HT5GDHC):** HT5GDHC is an insulated district heating network that is operated at 35°C supply and 30°C return temperature. The system acts as a heat source and heat sink for the building/flat level heat pump, which boosts the supply temperature to a level sufficient for fulfilling space heating, space cooling and DHW demands. The waste heat from the cooling operation is prioritized for fulfilling own DHW demands, via DHW storage tank. Any excess waste heat from the cooling operation is delivered into the 4GDHC network at the system supply temperature.
- **Low temperature 5GDHC (LT5GDHC):**
  LT5GDHC is an uninsulated district heating network that is operated around the soil temperature. The system acts as a heat source for the building/flat level heat pump, which boosts the supply temperature to a level sufficient for fulfilling space heating and DHW demands. The distribution temperature is assumed sufficiently low to fulfill the building cooling demands directly and impact of high soil temperature during the summer period is neglected.
- **Standalone heat pump:** The last variant is an air source heat pump, installed at a building level. The air source heat pump delivers heating and cooling for all thermal demands of the end-users.

In all the DH variants there is a central heat plant for regenerating the distribution network. The central heat plant consists of a utility sized heat pump, designed for fulfilling 90% of the annual demand, and a gas peak load boiler, designed for fulfilling the remaining 10%. Additionally, a dry cooler is considered for disposing of excess waste heat that cannot be used from the cooling operation.

2. Methodology

The following section contains a description of the data used for the analysis as well as the underlying assumptions and methodology of the paper. Calculations were performed in EnergyPlus, Matlab and Microsoft Excel. EnergyPlus was used for estimating the space heating and cooling demands of standard buildings in Italy, Matlab was used for dimensioning the pipe networks and thermal plants and estimating the system efficiencies for each heat supply system. Microsoft Excel was used for economic calculations and comparisons, based on the output from EnergyPlus and the Matlab calculation program.

2.1 Buildings

The buildings thermal demands considered in the analysis were simulated based on the generic buildings for Italy's middle climate zone, as specified in the Typology Approach for Building Stock Energy Assessment (TABULA) project [10]. The analysis assumes an area consisting of both existing and new buildings, where the existing buildings represent buildings from 1946 to 1960 and new buildings represent buildings built 2006 and later. Additionally, the buildings are divided into single-family and multi-family buildings, see **Figure 1**.

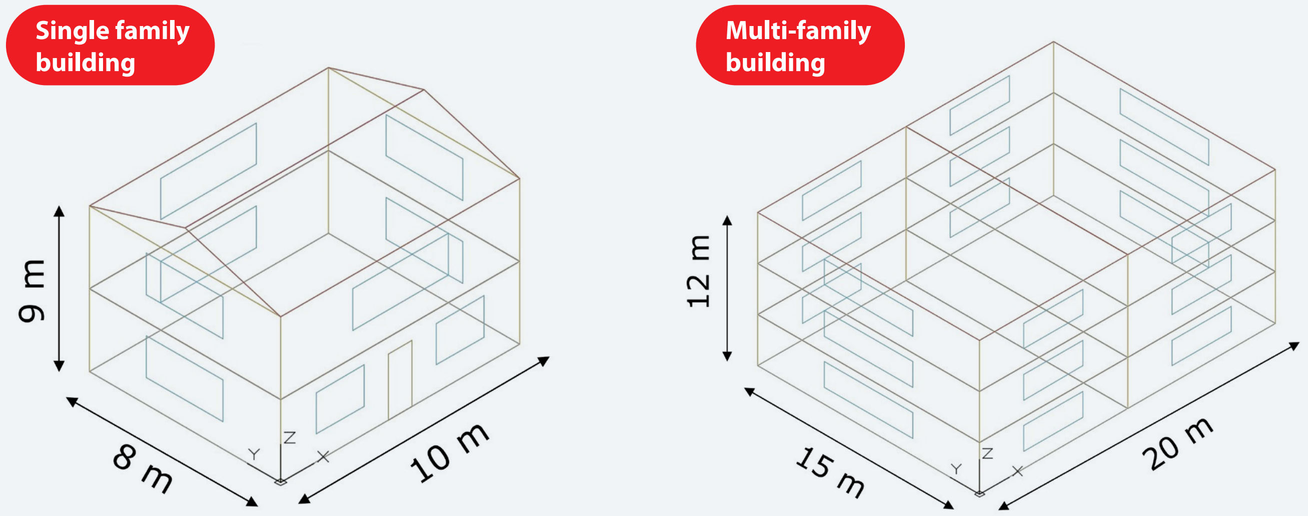

Figure 1. Left: Schematic of the single-family buildings. Right: Schematic of the multi-flat buildings.

The single-family buildings were modelled with a heated area of 160 m^2 and the multi-family buildings with heated area of 900 m^2, which is divided between 6 equal size flats. The building envelope parameters are given in **Table 1.**

Table 1. Parameters of the building envelop for the considered buildings.

BUILDING						ROOF		WALL		FLOOR		WINDOW		DOOR		SHGC
AGE	TYPE	COUNTRY	DATE	FLOOR AREA	CLIMATIC ZONE	SURFACE AREA	U	SURFACE AREA	U	SURFACE AREA	U	SURFACE AREA	U	SURFACE AREA	U	-
-	-	-	Year	m^2	-	m^2	W/ (m^2*K)	m^2	W/ (m^2*K)	m^2	W/ (m^2*K)	m^2	W/ (m^2*K)	m^2	W/ (m^2*K)	-
OLD	SH	ITA	1946-1960	160	E	84	2	432	1,5	160	2	86	5	2,4	3	0,7
	MH	ITA	1946-1960	900	E	300	2	630	1,5	900	2	126	5	2,4	3	0,7
NEW	SH	ITA	2006	160	E	84	0,3	432	0,3	160	0,3	86	2	2,4	1,5	0,3
	MH	ITA	2006	900	E	300	0,3	630	0,3	900	0,3	126	2	2,4	1,5	0,3

The simulation for the solar radiation through windows, $\dot{Q}_{sol}$, the heat transmission through the building envelope, $\dot{Q}_{env}$, and the heat transmission due to ventilation/infiltration and humidity control, $\dot{Q}_{ven}$, was performed with EnergyPlus using climate profile for Rome, "Roma-Ciampino 162390 (IGDG)".

Internal heat gains, $\dot{Q}_{int}$, from occupancy, appliances and lighting were modelled based on [25]. The DHW demand, $\dot{Q}_{DHW}$, was assumed 3 MWh/year/household. The daily aggregated profile of the DHW demand was based on **Figure 2**, which is based on [26] and [27].

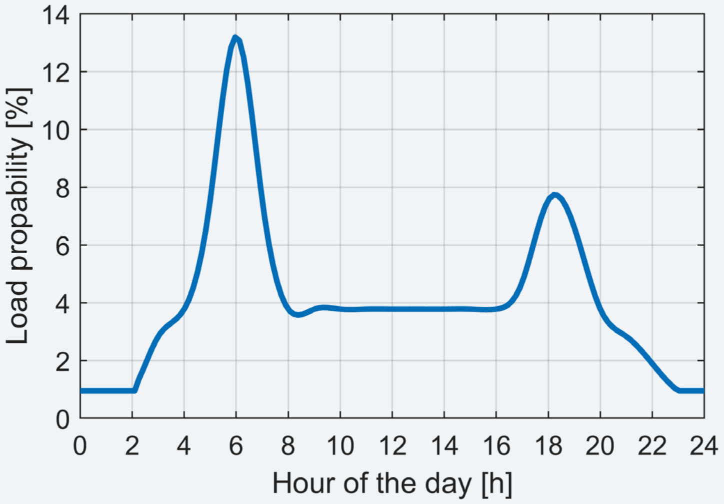

Figure 2. Daily aggregated DHW profile.

The energy balance of the building is provided by Eq. 1.

$$\dot{Q}_{sys}=\dot{Q}_{sol}+\dot{Q}_{env}+\dot{Q}_{ven}+\dot{Q}_{int}+\dot{Q}_{DHW}$$

Where $\dot{Q}_{sys}$ is the heat supplied/removed from the building.

The thermal demand of an existing and new multi-family buildings is shown in **Figure 3**. As can be seen from the figure there is generally slightly more cooling demand than DHW demand on a daily basis, meaning that in theory most of the cooling demand could be absorbed by the DHW demand in the building and only a minor part would need to be delivered into the ambient or the DH grid.

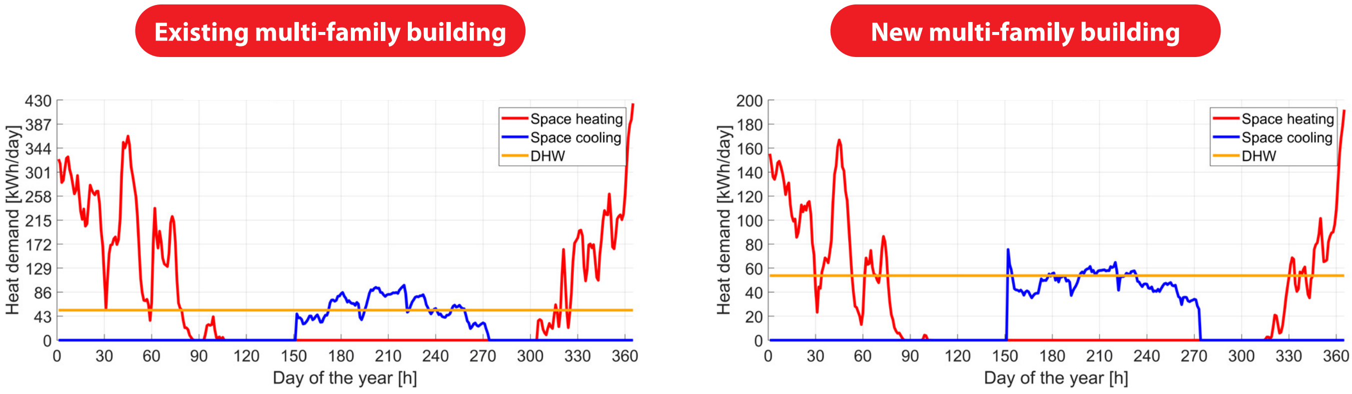

Figure 3. Thermal demands of existing (above) and new (bellow) multi-family buildings.

2.2 **District heating** heat interface units

The considered heat interface units (HIU) in the DH systems are dependent on the system design and how the cooling demand is fulfilled.

- **4GDHC:** The HIU has an integrated heat pump module (HPM), enabling the HIU to fulfill space heating, space cooling and DHW demands.
- **4GDH+AHP:** The HIU covers space heating and DHW demands. The cooling demands are assumed to be covered by individual air source heat pump (split unit) in each residential unit. The split unit is a one-point cooling entry and as such not fully comparable to the other DH variants.
- **HT5GDHC:** The HIU includes a heat pump for fulfilling the space heating, space cooling and DHW demands.
- **LT5GDHC:** The HIU includes a heat pump for fulfilling both the space heating and DHW demands. The cooling demands are fulfilled directly by the supply system, via a heat exchanger.

In the analysis all HIU's were dimensioned to for being able to fulfill the thermal demands with comparable comfort to the end-users. The schematics of the different DH HIU stations is shown in **Figure 4**.

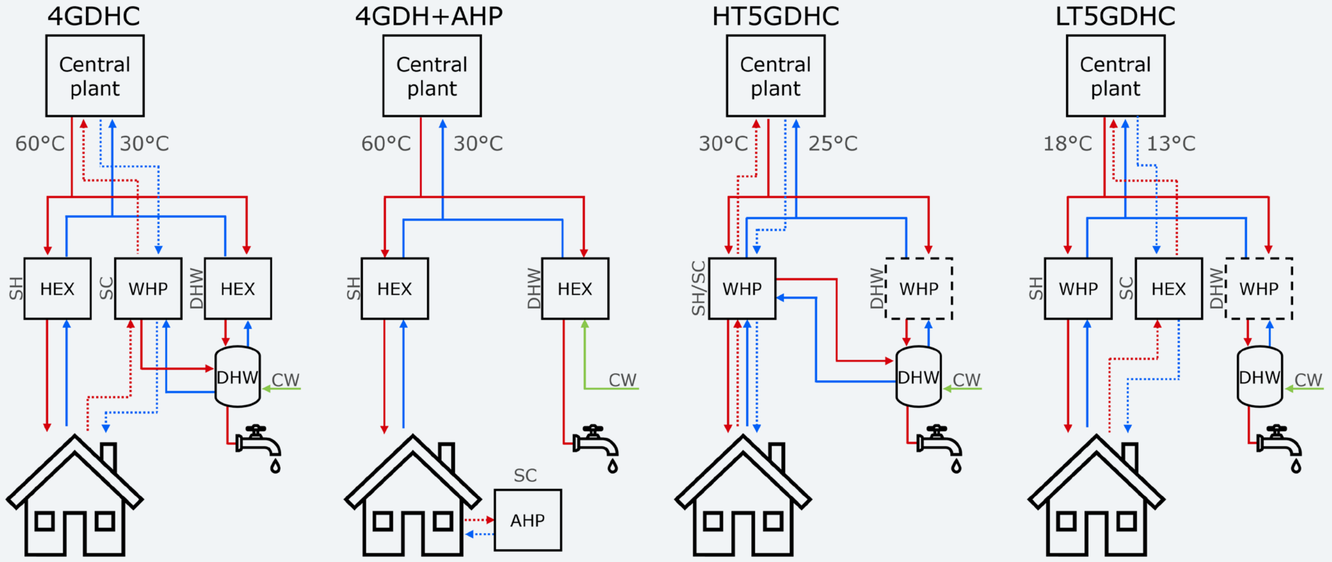

Figure 4. Schematics of the HIU for the different DH schemes. Dotted line arrows represent cooling demands and solid line arrows heating demands. SH represent space heating, SC represents space cooling, DHW represents domestic hot water, CW represents cold water, HEX represent a heat exchanger, WHP and AHP represent a water and air source heat pumps respectively. The dotted lines around the DHW WHP implies that it can be the same as the SH/SC WHP or a dedicated DHW WHP.

The technology data for the HIU's are shown in **Table 2**, where Capital Expenditures (CAPEX) includes the investment and installation of the unit, Operational Expenditures (OPEX) is the cost of operating and maintaining the unit, efficiency refers to the efficiency of direct usable heat supply and the Coefficient Of Performance (COP) indicate the useful thermal units per input electricity units. The data source for the 5th generation heat pump units is based on the Technology Catalogues published by the Danish Energy Agency (DEA) [28], where the equipment cost is based on the ground source heat pumps and the installation cost is based on air source heat pumps. For the 4th generation units, the data source is Danfoss.

Table 2. Technology data for the individual HIU in Denmark in 2020, extrapolated based on [28].

Type of system	Unit	CAPEX [€/unit]		Capacity [kW]	Lifetime [years]	Fixed OPEX [€/year]	Auxiliary power [kWh/year]
		Equipment	Installation				
4GDH	HIU	1,700	720	32	25	49	60
	AHP	1,200	400	5	12	50	0
4GDHC	HIU	5,050	1,020	32	25	130	60
	HPM			5	25		
LT5GDHC	SFH	4,200	1,600	13	20	280	60
	MFH	23,000	8,000	30	20	2,200	325
HT5GDHC	SFH	4,200	1,600	13	20	280	60
	MFH	23,000	8,000	30	20	2,200	325
AHP	SFH	4,460	1,610	13	16	280	60
	MFH	21,700	9,200	30	20	2,200	325

2.3 Coefficient of performance calculations for **end-user heat pumps**

The space heating and cooling installations considered in these analyses are water supplied fan coil units. The supply and return temperature to the fan coil units are 45°C and 40°C for space heating and 15°C and 20°C for space cooling. For the DHW part of the heat demand the analysis assumes a DHW storage tank charged at 65°C. The applied seasonal coefficient of performance for the end-user heat pumps are shown in **Table 3**.

Table 3. SCOP of end-user heat pumps for space heating and cooling for single-family houses (SFH) and multi-family houses (MFH) and the HIU efficiencies applied in the 4GDH and 4GDHC variants.

	Space heating		Space cooling to DH		Space cooling to DHW		DHW preparation		Space cooling to ambient	
	SFH	MFH	SFH	MFH	SFH	MFH	SFH	MFH	SFH	MFH
LT5GDHC	4.1	4.3	N/A	N/A	1.6	1.7	2.5	2.5	N/A	N/A
HT5GDHC	6.1	6.6	5.1	5.2	1.6	1.7	3.1	3.2	N/A	N/A
4GDH	0.96	0.96	N/A	N/A	N/A	N/A	0.96	0.96	3.0	3.0
4GDHC	0.96	0.96	1.6	1.7	1.6	1.7	0.96	0.96	N/A	N/A
AHP	3.5	4.0	N/A	N/A	1.6	1.7	2.0	2.2	3.0	3.0

2.4 Distribution network

The layout of the network was designed based on a neighborhood in Rome. The buildings connected to the network are a mixture of new and existing single-family houses and 3 story high multi-apartment buildings, each with 6 flats. The system connects 123 buildings, with 513 households to a central heat source, see **Figure 5**.

Figure 5. An overview of the distribution network layout.

The distribution network was dimensioned for each supply system, considering supply system specific conditions, such as the design distribution temperatures, simultaneity factors for both space heating and DHW demands, and the impact of local heat generation at end-user heat pumps in the 5th generation variants. The space heating simultaneity factors were based on Danish norms and the DHW simultaneity factors were based on Euroheat & Power recommendations [29], see **Figure 6**. The pipes were dimensioned for the peak demand, after taking into account the simultaneity factors, for each supply variant, using a maximum pressure drop of 150 Pa/m, ΔP_{max}, flow velocities of max 2 m/s, v_{max} and the design operating temperature. A description of the network dimensioning method is presented in [7].

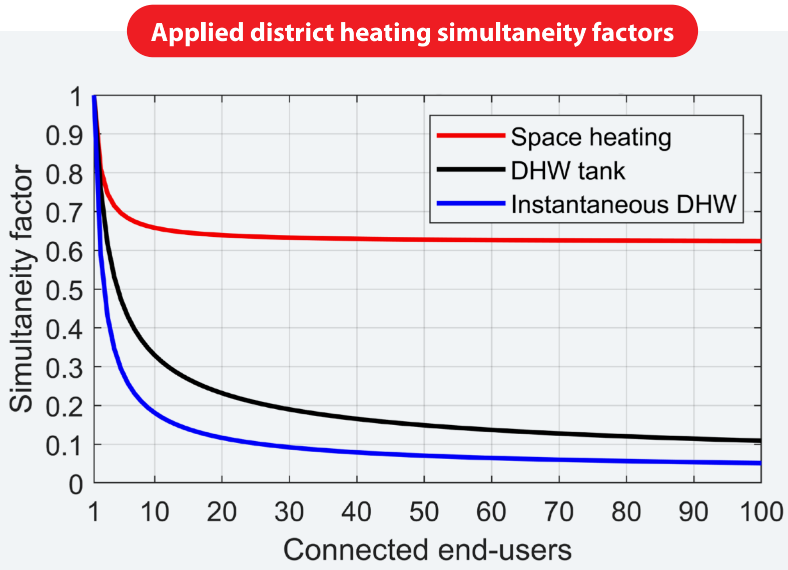

Figure 6. Applied simultaneity factors for space heating and DHW demands.

For the 4GDH, 4GDHC and HT5GDHC systems a standard series 2 pipe insulation, according to the EN253 standard, was applied. For the LT5GDHC system uninsulated pipe network was applied, as the operating temperature are assumed to be around the soil temperature.

The cost of establishing the insulated distribution systems were estimated based on project experiences in Danish outer city areas. To estimate the cost of an uninsulated pipe network the study takes the approach to discount the cost of establishing an insulated pipe network. The discount is based on the relative reduction in the trench volume when installing an equal dimensioned uninsulated pipe network. With this approach the cost of the establishing uninsulated pipe network is estimated to be ~40% less costly than an equal dimensioned insulated pipe network.

For all systems the economic lifetime of the pipe network is set to 40 years. Heat losses from the insulated pipe networks are estimated based on data sheets from Logstor A/S. In the case of the LT5GDHC the heat loss is neglected, on the assumption that the net annual heat loss and heat gains are on a similar level.

Although there will inevitably be high uncertainty around the cost of establishing the distribution grid it should be kept in mind that this uncertainty is shared with all considered supply systems, and as such the impact on the comparison is assumed insignificant.

2.5 Central heat plants

The central thermal plant considered in the analysis is based on three elements, an air source heat pump, dimensioned for 90% of the annual heating demand, a peak load gas boiler, dimensioned for the remaining 10% of the heating demand and dry coolers for dissipating the waste heat from the cooling operation that cannot be absorbed within the networks. The central thermal plant was sized for each supply system, for taking into account the impact from the building level heat pumps.

The technology data for the central thermal plant are shown in **Table 4**. The data is based on the DEA technology catalogue [30]. The SCOP of the central heat pumps is estimated based on the EnergyPlus standard climate data, the design operating temperature of each of the system variants and the thermal demands for each DH system variant. The SCOP for the LT5GDHC is particularly high as for significant part of the year the distribution network is assumed to be regenerated directly in the air to water heat exchangers. The reason for the 4GDH for having a higher SCOP than the 4GDHC is due to the DHW load during the cooling season, which is low in the 4DHC case due to end-user own waste heat consumption for DHW purposes.

Table 4. Technology data for central heat plants and heat exchanger stations in Denmark in 2015 [30].

Type of unit	CAPEX [M€/MW]	Unit efficiency & COP [%]	Lifetime [years]	Fixed OPEX [€/MW/year]	Variable OPEX [€/MWh]
Central air source heat pump	0.95	LT5GDHC - SCOP: 15.0 HT5GDHC - SCOP: 7.3 4GDH - SCOP: 5.3 4GDHC - SCOP: 5.0	25	2,000	2.19
Natural gas peak load boiler	0.06	103% (LHV)	25	1,950	1.1

2.6 District heating **operation fees**

To enable comparison with standalone heating and cooling solutions the following costs associated with operation of district heating systems are included in the estimation of the thermal supply cost for all DH variants. These costs are the average costs occurring at Danish district heating systems.

1. Administration cost: 12 EUR/MWh.
2. Heat metering:
   75 EUR/year/connection

These costs are adjusted in the analysis to Italy, based on Eurostat Purchasing Power Parities (PPP).

2.7 Transferring **Danish price levels to Italy**

As the analysis is relying on economic data from Denmark, which is a high-cost country, it is necessary to adjust the cost levels to Italian levels. The cost levels are adjusted using Eurostat published PPP, see [31], to transfer the economic data from the DEA technology catalogues to Italy. The economic data is further adjusted according to the price level changes from the year of data in the technology catalogues to the year of the analysis. Table 5 shows the applied PPP's for Denmark and Italy as published by Eurostat.

Table 5. Eurostat Denmark and Italy PPPs.

PPP factors (EU27_2020 = 100)	DK 2015	DK 2020	IT 2015	IT 2020	IT 2021
Machinery and Equipment	117.6	114.9	97.9	98.0	97.5
Civil engineering works	133.0	126.7	89.8	81.6	80.7

2.8 Energy prices

Unlike individual building level heating solutions DH has the advantage of economy of scale, large volumes and connecting to high voltage grids, which enables it to assess better energy tariffs than individual buildings. For transparency Eurostat energy prices, excluding recoverable taxes and levies, are applied in this analysis, see [32], [33] and [34]. The energy cost levels applied in this analysis are shown in **Table 6**. Due to general unpredictability of future energy prices the analysis assumes that the price levels are fixed for the future, either as a "normal" or as a "crisis" operation.

Table 6. Energy costs, excluding VAT and other recoverable taxes and levies, applied in the analysis.

	Normal cost levels 2020-S1 [EUR/MWh]	Crisis cost levels 2022- S2 [EUR/MWh]
Household electricity: 5-15 MWh/year	192.2	317.8
Household electricity: >15 MWh/year	169.3	323.5
Non-household electricity: 500-2,000 MWh/year	150.3	337.2
Non-household natural gas: 1,000 – 10,000 GJ/year	43.9	127.6

In respect to green heat supply the CO_2 emissions from the natural gas consumption can be offset via green certificates. The cost of green certificates would add to the cost of DH heat generation. As an example, the average cost of emission allowances in EU in 2021 was around 85 EUR/ton[1]. Based on IPCC emission factors the use of natural gas results in 202 kg CO_2 emission per MWh [35], which results in an additional cost of 17.2 EUR/MWh heat from the gas boiler. The additional cost of green certificates would in the considered setup amount an extra cost of around 1.7 EUR/MWh.

2.9 District heating duration curves

Due to the different building level HIU setups the thermal demands to the DH systems will vary. This is due to both the COP of the building level heat pumps and the possibility to recover the waste heat from the cooling operation. In general, the higher the building level heat pump COP is the closer the duration curve of the 5th generation systems becomes to the 4th generation systems. Figure 7 shows the DH system duration curves for the considered DH variants.

District heating duration curves

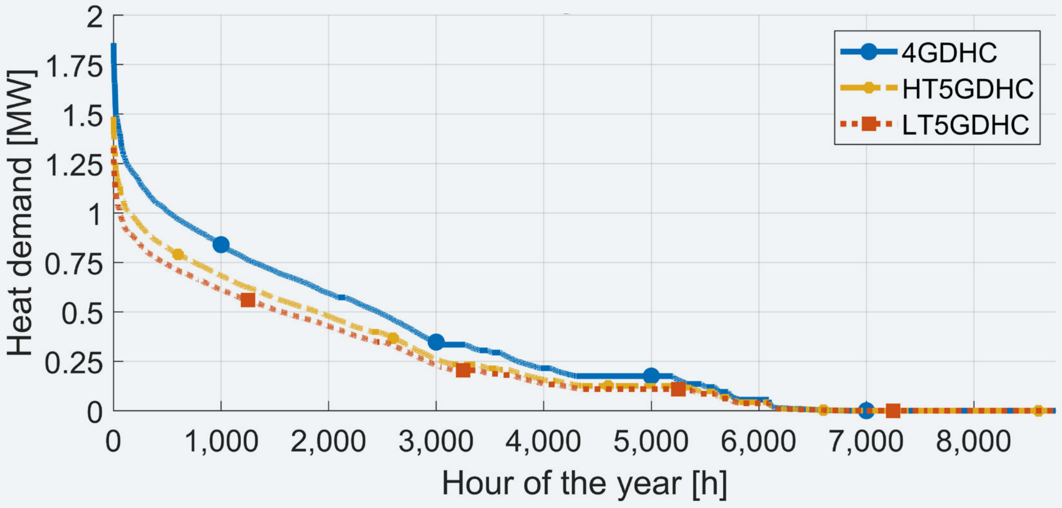

Figure 7. Duration curves for each of the DH system variants.

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[1] https://ember-climate.org/data/data-tools/carbon-price-viewer/

2.10 **System** boundaries

The system boundaries the analysis include the heat plant, the distribution pipeline, and the end-user HIU. The included costs in the analysis are the cost of installing, operating and maintaining:

1. The central heat plants.
2. The distribution pipe network.
3. The end-user HIU's.
4. Administration and billing costs.

The analysis does not consider different business models and potential profit margins for the DH system operator. The analysis is further simplistic in the way that it is not considering potential cost-optimization potentials that DH might have from utilizing local energy sources or taking advantages of load shifting potentials and fluctuating power prices. The cost estimation of the building level air source heat pump is on the other hand the total cost, as the electricity cost is the end-user cost, excluding VAT.

2.11 **Cost** comparison

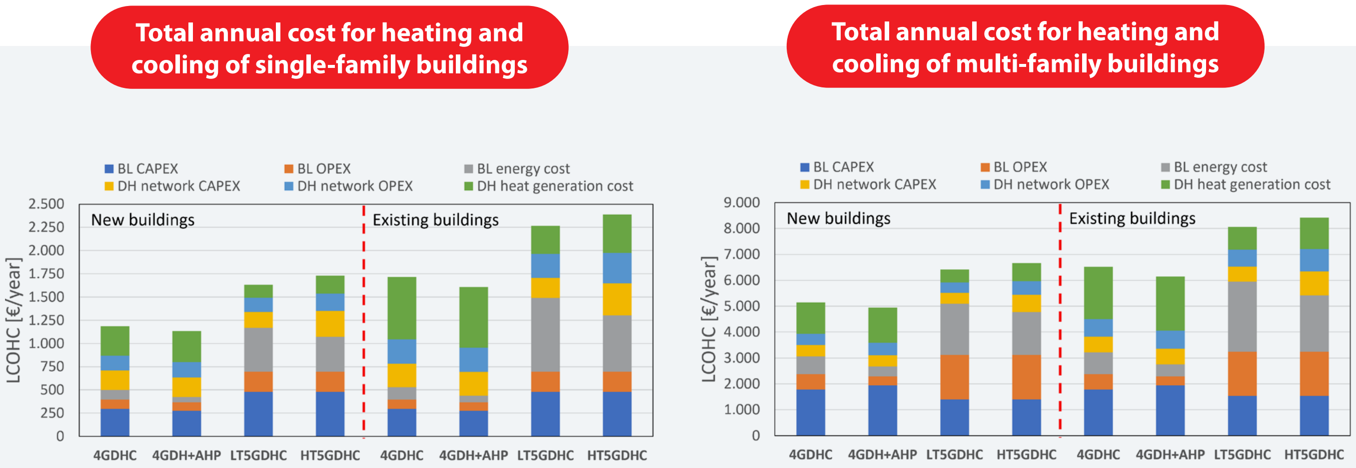
The different thermal supply variants are compared based on the total cost of heating and cooling. The total cost is based on the annualized CAPEX, OPEX, driving energy cost and unit efficiency of each system component. The annualization of component costs is achieved by using Eq. 6.

$$CAPEX_a = \mathrm{CAPEX}/((1-(1+i)^{-T})/i)$$

Where *a* denotes annualized, *T* is the technical lifetime of the investment [years] and i is the cost of capital [%]. The economic analysis assumes 3% cost of capital for all investments, which according to [36] is approximately the social cost of capital.

3. Results

The results of the analysis for a "normal" energy scenario are shown in **Figure 8**. The figure shows the annualized cost of heating and cooling the four different buildings considered, being supplied by the four different DH variants.



Total annual cost for heating and cooling of single-family buildings

Total annual cost for heating and cooling of multi-family buildings

Figure 8. Levelized cost of heating and cooling given the 2020-S1 energy costs levels for single family buildings (left) and multi-family buildings (right). The notion BL remarks cost occurring at the building level, the DH remarks the cost occurring at the DH level.

3.1 Economic comparison

The key driver for the economic advantages of the 4G variants over the 5G variants is the lower cost of input energy, driven by the favorable tariffs offered to non-residential consumers. The second main influencing parameter is the cost of the HIU's, which is lower in the 4G variants compared to the 5G variants.

The results further show that as the building stock becomes more energy efficient the 4G variants will increase its cost effectiveness compared to the 5G variants, again driven by lower cost of driving energy but also due to a generally lower investment cost. The annual cost of heating and cooling from standalone heat pumps is shown in **Table 7**.

Table 7. Annual cost of heating and cooling in EUR/year from standalone air to water heat pump solutions.

Energy price data	SFH existing	SFH new	MFH existing	MFH new
2020-S1	1.540	1.170	6.560	5.550
2022-S2	2.160	1.550	8.690	7.110

3.2 Sensitivity of input parameters

When considering the sensitivity of the results the main elements to consider is the building HIU's and the power costs. Other elements of the system, central heat plant and the distribution network, both have small impact on the annualized cost and will generally have the same relative impact on each of the DH supply variants.

The HIU's impacts the results through the capital expenditures (CAPEX), operational expenditures (OPEX), technical lifetime and unit efficiencies. As traditional DH substations are mature technologies the sensitivity analysis of the HIU's is focused on the impact if the parameters of the 5G HIU's are made more favorable. The consider changes were following:

1. 20% reduction in CAPEX
2. 50% reduction in OPEX
3. Technical lifetime increased by 5 years
4. Heat pump COP increased by 20% (by factor 1,2)

The cost of the drive energy is a major influencer on the results, particularly the cost of electricity. The key difference between the 4G and 5G variants is the amount of electricity consumed in the buildings, see **Table 8.**

Table 8. Share of total annualized thermal cost due to the total drive energy, energy consumed in the building (BLS) and energy consumed in the DH system.

	New SFH			Existing SFH			New MFH			Existing MFH		
	Total	BLS	DH	Total	BLS	DH	Total	BLS	DH	Total	BLS	DH
4GDHC	33%	3%	30%	47%	4%	42%	31%	5%	26%	40%	7%	33%
4GDH+AHP	36%	5%	31%	47%	5%	42%	36%	8%	28%	42%	8%	35%
LT5GDHC	42%	32%	9%	52%	38%	14%	40%	32%	8%	45%	34%	11%
HT5GDHC	37%	24%	13%	46%	27%	19%	37%	25%	11%	41%	26%	15%

To assess the impact of the drive energy cost two scenarios were considered:

1: Assuming equal household and non-household power prices in the base case.
2: Changing the input energy prices from the Eurostat S1-2020 to S2-2022.

The sensitivity of the result for the HIU's parameters and scenario 1 for the drive energy costs are shown in **Figure 9**. As the figure shows the results are quite robust, even when all the considered input parameter changes are combined the 4GDHC has lower annualized cost of heating than the 5G variants.

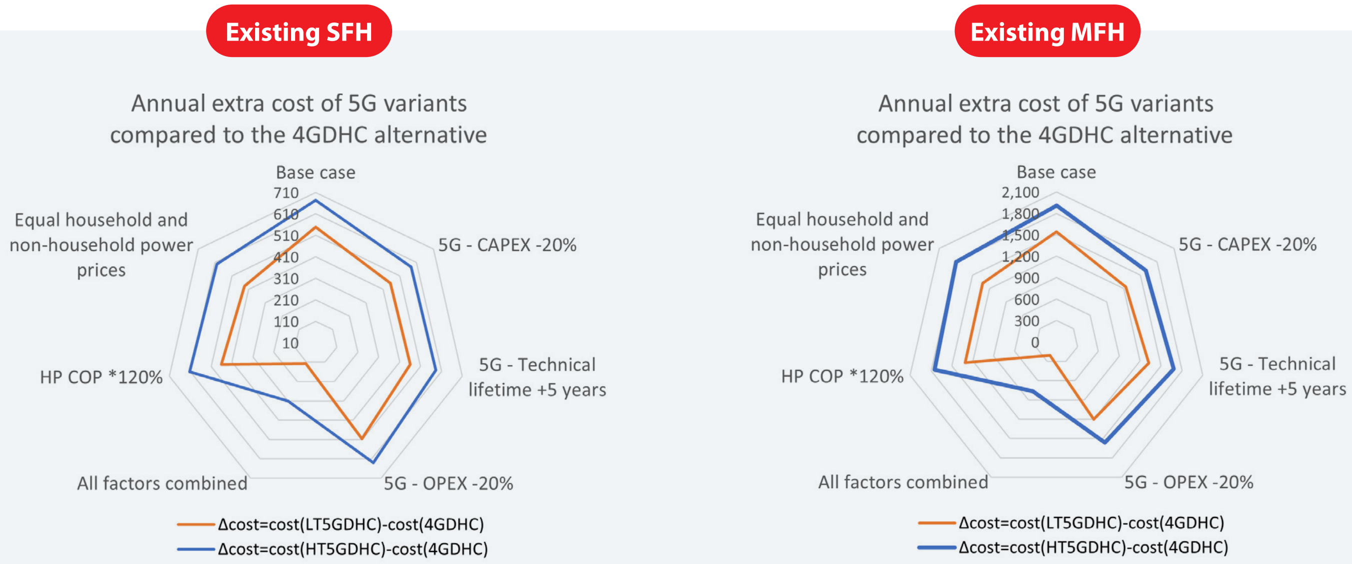


Figure 9. Impact of reduced costs and increased performance of 5G HIU's and equal household and non-household power costs on the annualized cost difference of 5G variants and the 4GDHC system. Left figure is for existing SFH and right figure is for existing MFH.

Scenario 2 represents a special situation, specifically the energy crisis resulting from the Russian war on Ukraine. For combating energy poverty, the Italian government subsidized the power cost for households [37], leading to the situation that the household power cost was lower than non-household power costs. As **Figure 10** shows even in these unusual situations the 4GDHC is more economical than the 5G variants.

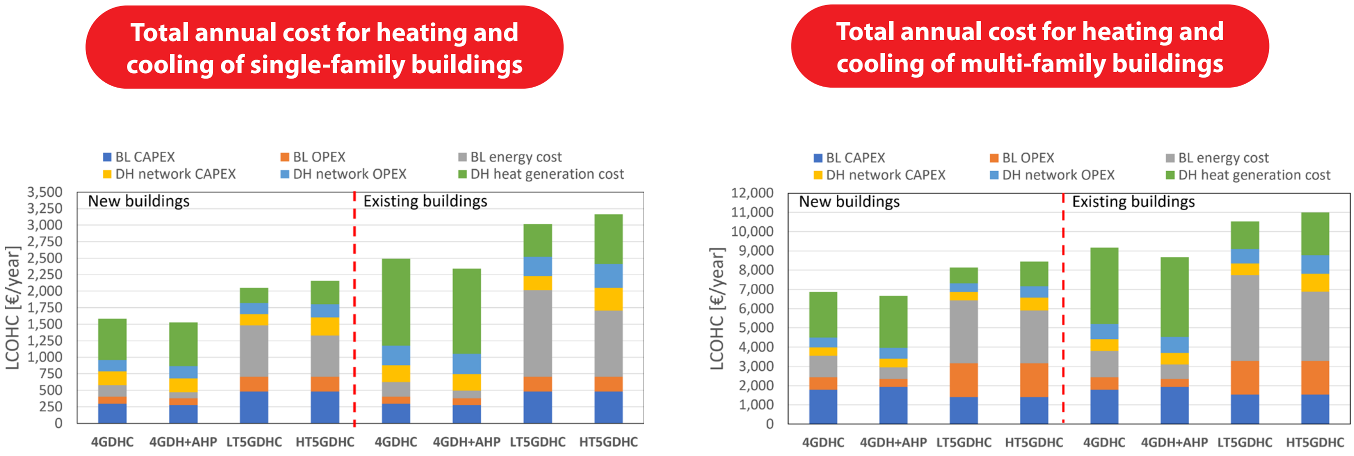


Figure 10. Levelized cost of heating and cooling when applying 2022-S2 energy cost levels. Left: Single family buildings. Right: Multifamily buildings.

4. Conclusions and discussions

This paper compares the annualized cost of four DH variants for fulfilling heating and cooling demands, 4GDH and end-user air source heat pump, 4GDHC, HT5GDHC and LT5GDHC using a case study in Rome, Italy.

The analysis shows that the economy of scale obtained by centralized heat generation in 4G systems, provides significant competitive advantage over 5G systems, which rely on end-user heat generation. The results are consistent for both existing and new buildings.

A sensitivity analysis of key parameters that could influence the results, economic and efficiency parameters of the building level HIU's and power prices shows that the 4G systems have robust advantage over the 5G systems.

When comparing the DH variants with standalone heat pump applications the 4G systems are on a similar cost level. However, with the 4G systems there are many possibilities to optimize the heat production as well as utilizing alternative heat sources that might be available in proximity of the DH area. Diversifying the heat supply in the 4G systems would further significantly increase the resilience of the heat supply system, which would not be possible in the 5G systems, which are inherently dependent on instant power access. In respect to a supply crisis, as occurred due to the Russia war on Ukraine, 4G systems would offer the possibility to bring alternative heat generation units to tackle the energy supply shortage.

In combination with thermal energy storages the DH could further significantly optimize the heat production by generating heat during off peak periods. This would not be possible to the same extent with individual heat pumps. This would further significantly reduce the required investment in the power infrastructure in case the heat supply is electrified, as the heat generation can be decoupled from the heat demand to much larger extent in the 4G systems than in the 5G systems. Additional benefit of the centralized nature of the 4G systems is the possibility of offering large scale power balancing services, either by offering flexible central heat pump operation or by instant power balancing with large scale electric boilers.

Although greenhouse gas emissions have not been part of this analysis the authors recognize its importance and the influence it may have on the decision on what kind of thermal supply system to apply in the future, and hence it deserves some thoughts. As heat pumps are the major heat supply solution in all systems the CO_2 emissions will be dependent on the CO_2 factor of the electricity grid. In addition to CO_2 emissions the possibility of leakage of refrigerants is much higher in a system with vast number of building level heat pumps than in large professionally operated, and continuously monitored, utility sized heat pumps.

The 4G variants have further a significant advantage, that was not evaluated in this study, which is the possibility to apply large scale thermal energy storages for shifting the electricity consumption from high CO_2 concentration periods to low CO_2 concentration periods. Further, due the insulated pipe network the 4G systems are better positioned take energy efficient advantage of local waste heat streams than the 5G systems, which would again lead to lower CO_2 emissions.

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