Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Testing of a prototype substation for a 5th generation district heating and cooling network

To cite this article: G Martinazzoli *et al* 2025 *J. Phys.: Conf. Ser.* **2940** 012023

Journal of Physics: Conference Series **2940** (2025) 012023 doi:10.1088/1742-6596/2940/1/012023

Testing of a prototype substation for a 5th generation district heating and cooling network

G Martinazzoli[1,2]*, D Pasinelli[2], A M Lezzi[1] and M Pilotelli[1]

[1] Dipartimento di Ingegneria Meccanica e Industriale, Università degli Studi di Brescia, Brescia 25123
[2] A2A Calore & Servizi S.r.l., Brescia 25124

*E-mail: g.martinazzoli002@unibs.it

Abstract. 5th generation district heating (5GDH) networks can be an effective way to increase the penetration of renewable energy and achieve decarbonisation in the heating and cooling sector. This article describes 5GDH networks by focusing on network substations, the complexity of which increases compared to a conventional district heating substation due to the presence of a decentralised heat pump and a bidirectional pumping system. The purpose of the article is to show the components and layout of a prototype substation and a pilot network, realised to recover low-temperature waste heat and cover the heating and cooling demand of a building. The results present the performance and energy consumption of the prototype during the first heating season in which the prototype is in operation. The prototype was tested through two kinds of tests: tests under design and off-design conditions. In tests under design conditions, the average COP of the heat pump is between 3.3 and 4.2, while the values drop to 2.6 – 3.1 considering the overall COP. The off-design tests were performed to define the performance of the heat pump for a wider temperature range. For these tests, the COP is between 2.9 and 6.1.

1. Introduction

As in the electricity sector, where the transition to more sustainable energy sources is taking place, various efforts are also being made in the heating and cooling sector to replace fossil fuels as primary energy sources. The role of the heating and cooling sector within the energy field is crucial, as it is responsible for over 50 % of global final energy consumption and one third of carbon emission [1]. In Europe, the 37 % of greenhouse gasses emissions comes from activities related to heating and cooling [2]. This sector is characterised by a slower decarbonization process, especially if compared to the electricity sector. However, innovative solutions are also being developed in the heating and cooling sector to achieve a transition to sustainable energy sources, and one of the main drivers in this direction is the district heating (DH) [3].

In conventional DH systems, heat is generated in thermal plants, such as cogeneration, waste-to-energy and renewable energy plants, in order to have the advantages of centralised heat generation, as well as wasted heat can be also recovered from industrial processes. Thus, plant efficiency in energy conversion is higher, whereas pollutant, CO2 and consumption of primary energy sources are lower, in line with the European strategy for efficient energy use for

Journal of Physics: Conference Series **2940** (2025) 012023 doi:10.1088/1742-6596/2940/1/012023

heating and cooling [4]. The generated heat is distributed at a temperature high enough to connect the DH network directly to the end users through heat exchangers.

Along with the development of conventional DH, which has evolved to the 4th generation [5], an innovative generation of DH is being developed to overcome some of the limitations of conventional networks such as the requirement of high-density population areas, heat losses that count for about 20 % in conventional DH [6], separation from the power grid, as well as the limitated application of renewable energy. In this kind of DH networks, called 5th generation DH (5GDH), heat is shared at a temperature close to ground temperature, typically between 10 – 30 °C [7]. The low temperature of the heat transfer fluid in the network allows the use of naturally available low-temperature heat sources, such as shallow geothermal energy [8], or the recovery of low-temperature heat, wasted from industrial processes [9]. The low temperature of the heat in the network does not enable a direct connection between the 5GDH network and the users via heat exchangers as in conventional DH, but requires the installation of decentralised heat pumps in the network substations. Decentralised heat pumps require electricity to generate heat or cold for the building, allowing the connection of the power grid to the DH network, as depicted in Figure 1. Figure 1 shows the differences between a conventional DH network and a 5GDH network, in which the low-temperature of the heat shared with the network and the electricity used by heat pumps facilitate the penetration of renewable energy. Most of the energy is used to supply the grid substations, which are strategic network hub. Another advantage is that the same infrastructure can be used to cover the heating and cooling demand of the buildings connected to the network, creating a district heating and cooling system.

On the other hand, in the 5GDH the complexity of the network substation increases due to the presence of a heat pump and the possibility of having a heating and cooling configuration that leads to considering a user as a heat consumer in the heating configuration, but also as a heat producer, in cooling configuration. Another complication is the decentralised pumping system: a pump is installed in each substation to pump the flow to the heat pump evaporator to generate the required heat to the condenser, in heating configuration. In addition, pumping costs are higher than in the conventional DH network, where the pumping system is centralised, due to the low temperature difference between the supply and return line of the network.

As this is a new and potentially revolutionary topic, some papers in literature refer to this kind of networks with techno-economic evaluations [6], others propose different kinds of low-temperature heat sources [9], a few focus on the use of heat pumps in 5GDH, explaining the main parameters that should be optimised [10] or even regarding the developments that heat pump manufacturers should implement to improve performance in 5GDH [7]. However, authors do not know any article in which the layout of the substation for 5GDH network, including the pumping system, as well as the related energy consumption and performance analysis for a real case are deeply described. Therefore, this paper aims to describe the 5GDH substation layout adopted for a prototype of a real case study and a pilot 5GDH network. The prototype substation serves a real building with a heating and cooling demand and it is equipped with a measurement system to acquire data to analyse the performance and energy consumption of the substation. In this way, it is possible to evaluate and verify the proper operation of the 5GDH substation and to collect data to evaluate the possibility of deploying this kind of network on a large scale.

The paper is structured as follows: after a brief introduction in Section 1, Section 2 describes the configuration of the prototype substation and how it will be tested. Section 3 shows the

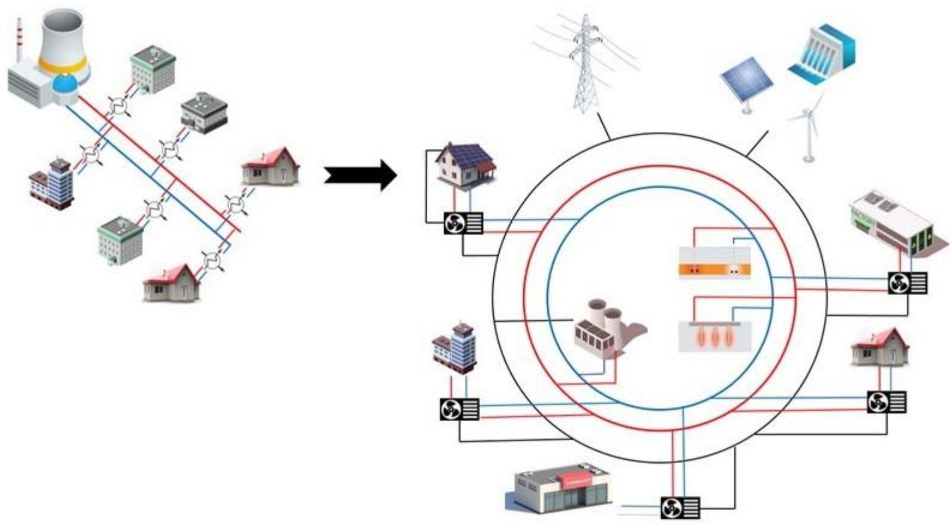

Figure 1. Difference between conventional DH (on the left) and 5GDH (on the right) network.

substation energy consumption results for the first heating season and an analysis of the performance of the heat pump installed in the substation. Section 4 presents the conclusions and a description of the future works on the prototype substation.

2. Materials and methods

The project concerning the development of a prototype substation for a 5GDH network has been carried out in cooperation between the University of Brescia and the company A2A Calore & Servizi. The city of Brescia has an extensive and capillary conventional DH network of more than 670 km of double pipes. This DH network is managed by A2A Calore & Servizi, which is interested in the development of new solutions to decarbonize the conventional DH networks and in the development of innovative DH such as the 5GDH.

The prototype has been installed inside the "Centrale Nord" in Brescia, a thermal plant of A2A Calore & Servizi that also houses chillers that feed a district cooling network and dissipate the heat produced through evaporative towers. Therefore, this site was selected due to the presence of low-temperature waste heat from the chillers and the presence of a building with heating and cooling demand, where the offices and control room of the plant are located. The prototype substation recovers the low-temperature heat wasted by the chillers through a 5GDH pilot network, supplying the heating and cooling demand of the building inside the Centrale Nord. Figure 2 shows the components of the prototype substation, which are:

- Gas-side reversible heat pump (HP)
- Bidirectional pumping system on 5GDH network (P-1; M3V-01; M3V-02)
- User pumping system (P2; P3)
- Inertial thermal energy storage (TES)
- Heat exchanger (HE).

A gas-side reversible heat pump has been selected to cover the heating and cooling demand of the building. The heat pump consists of two separated refrigeration circuits with a fixed-rpm scroll compressor for each one. The refrigerant R134a was selected as the best choice for this specific case study, as explained in [11] where the design phase of this project is well described.

The bidirectional pumping system is realised with a couple of motorised three-way valves and a pump (P-1), which is not equipped with an inverter, so that the flow rate in the pipes connecting the heat pump to the network is regulated by the FCV-01 motorised valve. In the heating configuration, the two three-way valves are opened in the main direction (ab-a) to pump water from the highest temperature line of the 5GDH network to the evaporator of the heat pump and then pumped it into the lowest temperature line of the grid. Conversely, in the cooling configuration, the three-way valves vary the set-up (ab-b) to pump water from the lowest temperature line and pump it, after passing through the chiller condenser, to the highest temperature line of the grid. In this way, the substation operates as a thermal prosumer, taking heat from the network in heating configuration and releasing heat to the grid in cooling configuration.
The inertial thermal energy storage has been adopted to decouple the heating and cooling demand from the heat pump and to enable an increase in heat pump performance.
Instead, the heat exchanger has been only installed in the substation prototype and will not be replicated when the prototype will be scaled up. The heat exchanger is being used to increase the temperature range on 5GDH side during the testing phase. Through the heat exchanger, the temperature of the 5GDH network, mostly between 18 and 20 °C during the winter, is increased up to 40 °C at the inlet of the heat pump evaporator, using heat from the thermo-hydraulic circuit itself. The reason for monitoring heat pump performance over a wider temperature range is to test the possibility of suppling the 5GDH network with different kind of low-temperature heat sources, available at different temperatures. The upper water inlet limit temperature has been set at 40 °C as a compatible limit with the 5GDH networks described in the literature and the sources available in Brescia.
The main role of the two motorised three-way valves is to allow the change of the flow direction in the network without reversing the direction of the flow in the evaporator or condenser. Moreover, the three-way valves (M3V-01, M3V02) can be used to test the heat pump at lower temperatures compared to those of the evaporative towers. Indeed, with an intermediate degree of opening, they can mix the flow entering the heat pump evaporator with the flow leaving the evaporator, resulting in temperature at the inlet of the evaporator in the range of 10-20 °C.
The nominal thermal capacity of the heat pump is 100 kW. The pipes of the 5GDH network have a diameter of 300 mm and are made by uninsulated carbon steel, as well as the pipes connecting the grid to the substation, which have a diameter of 80 mm. While the pipes of the intermediate circuit, between the heat pump condenser and the inertial storage tank, are made of insulated carbon steel, again with a diameter of 80 mm, as well as the pipes of the circuit connecting the inertial storage tank to the building's thermo-hydraulic circuit manifolds. The inertial storage tank, with a capacity of about 1000 l, is also insulated. The insulation is made with an extruded and vulcanized synthetic rubber (elastomer) foam suitable for insulating both heat and cold.

Figure 2 also shows the measurement system installed in the substation, consisting of flow meters (FT), temperature probes (TE) electricity and thermal energy counters (JQI). Specifically, four wires Pt500 temperature probes in the supply and return lines with magnetic-inductive (MID) flow meters and thermal energy counters are installed on the pipes of the network connection circuit (1), the intermediate circuit (2) and the building circuit (3). In addition, there are two electricity energy counters, one dedicated to the two heat pump compressors and the

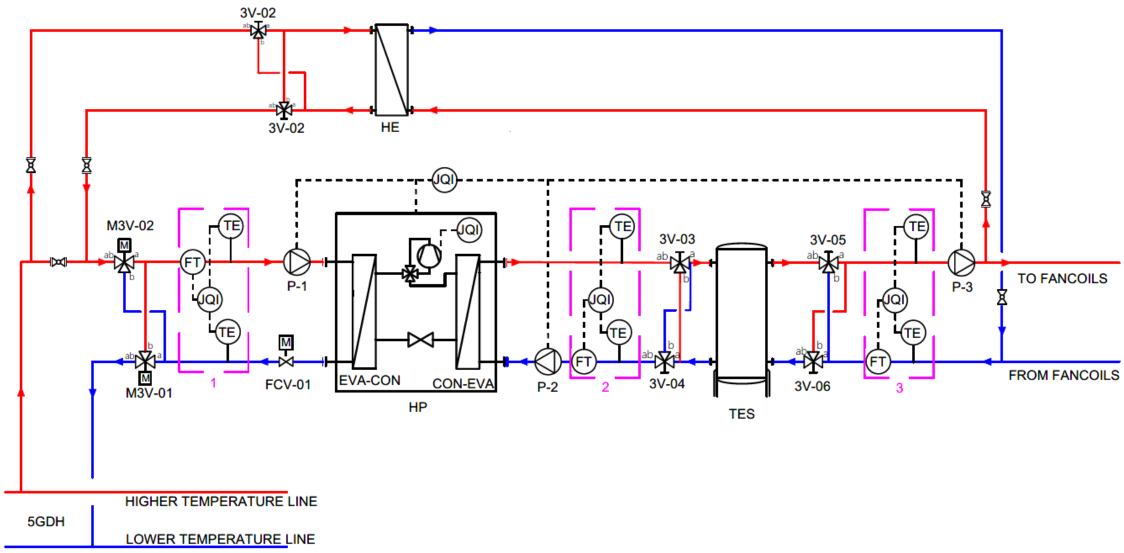

Figure 2. Process flow diagram of the prototype substation.

second one measuring the total amount of energy consumed by the substation prototype, including pumps and auxiliaries.

The COP is calculated as the ratio between the thermal power measured in the intermediate circuit (2) and the electricity absorbed by the heat pump compressors, while the global COP (GCOP) as the ratio between the heat supply to the building and the total electricity absorbed by the prototype substation. The former parameter does not take into account heat losses related to the building's thermo-hydraulic circuit and the energy consumption of pumps and other auxiliaries, but only defines the performance of the heat pump.

Two different kinds of tests were developed to analyse the performance of the 5DGH substation: tests under design conditions and under off-design conditions. The tests under design conditions are used to evaluate the energy consumption by the substation during the first heating season 2023-2024, taking into account the energy absorbed by the heat pump and the network pump (P1) under designed conditions, i.e. using the waste heat available from the centralised chillers at evaporator and condenser temperatures is in line with the temperatures required by the building's fancoil system. The tests under off-design condition were performed to evaluate the performance of the heat pump at different temperatures at the heat pump evaporator and condenser through the heat exchanger, the three-way valves and the variation of the condenser setpoint temperature. In this way, different kinds of waste heat (evaporator) and different kinds of thermo-hydraulic system (condenser) can be simulated. The data acquisition system has been developed to historise measurements with a sampling rate of one minute.

3. Results and Discussion

For the design tests, energy consumption has been evaluated during 24 hours for 64 days from December 21st to March 31st, and off-design tests have not been performed on these days.

The results of these tests for different temperatures at the heat pump condenser in the range between 49 and 60 °C are shown in Table 1, where the average values and standard deviation of the inlet evaporator temperature *(T_{eva})*, the outlet condenser temperature *(T_{con})*, the outdoor room temperature *(T_{out})*, the heat output to the condenser *($\dot{Q}_{con}$)*, the power input to the heat pump compressors *($\dot{W}_{hp}$)*, the power input to the network pump *($\dot{W}_{np}$)* and the *COP* are represented. Each row in Table 1 relates to a single day and has been obtained by considering only those instants of time when the heat pump was in operation during 24 hours, for a total of six days chosen as indicative among the 64 of the heating season due to the different temperatures at the condenser outlet and outside. In Table 2 are reported the 24-hour consumption for the six days of Table 1, in the same order. Specifically, Table 2 shows: the heat supplied to the building *(Q_{bui})*, the heat supplied to the heat pump condenser *(Q_{con})*, the electricity absorbed by the heat pump *(W_{hp})*, the electricity absorbed by the network pump (W_{np}), the total amount of electricity absorbed by the substation *(W_{tot})* and the overall *COP (GCOP)*.

Table 1. Average values and standard deviation of substation performance in steady-state conditions.

T_{eva} (°C)	T_{con} (°C)	T_{out} (°C)	$\dot{Q}_{con}$ (kW)	$\dot{W}_{hp}$ (kW)	$\dot{W}_{np}$(kW)	COP
18.7 ± 0.4	49.0 ± 0.3	8.7 ± 3.5	52.4 ± 2.5	12.5 ± 0.6	2.2 ± 0.6	4.2 ± 0.1
18.8 ± 0.4	51.0 ± 0.3	8.3 ± 1.2	52.1 ± 1.0	13.0 ± 0.1	2.3 ± 0.4	4.0 ± 0.1
18.6 ± 0.2	53.6 ± 2.4	8.3 ± 2.1	51.3 ± 4.2	13.5 ± 1.3	2.4 ± 0.4	3.8 ± 0.2
18.6 ± 0.1	55.7 ± 0.5	7.6 ± 0.3	51.1 ± 3.4	14.1 ± 0.9	2.5 ± 0.6	3.6 ± 0.1
18.4 ± 0.2	57.7 ± 0.5	7.6 ± 0.5	50.8 ± 1.0	14.8 ± 0.2	2.1 ± 0.3	3.4 ± 0.1
18.0 ± 0.3	59.4 ± 0.6	2.5 ± 3.6	50.5 ± 2.1	15.3 ± 0.6	3.0 ± 0.2	3.3 ± 0.1

Table 2. Energy consumption of the prototype substation for the 6 days of Table 1.

Day	Q_{bui} (kWh)	Q_{con} (kWh)	W_{hp} (kWh)	W_{np}(kWh)	W_{tot}(kWh)	GCOP
February 15th	450.6	474.9	109.9	23.9	145.7	3.1
March 28th	367.3	396.5	96.2	19.8	128.0	2.9
February 24th	454.3	472.4	121.7	24.3	158.0	2.9
December 31th	633.2	664.5	180.5	37.4	229.9	2.8
January 7th	619.2	648.0	183.8	38.0	233.9	2.7
January 13th	850.0	881.0	263.7	55.8	331.5	2.6

Under design operating conditions, only one compressor of the two heat pump compressors operates, because the average building demand is between 20-40 kW and the heat pump condenser can supply more than 50 kW, depending on the temperature setting at the condenser outlet. The heat supply to the condenser cannot be modulate due to the use of compressors without inverters for the heat pump, so the heat output of the heat pump can only be modulated by switching the compressors on or off and using the inertial storage.

Each bar in Figure 3 shows the sum of the daily amount of electrical energy absorbed by the heat pump (in blue), by the network pump (in orange) and by the auxiliaries (in yellow) to supply heat to the building, represented on the x-axis, for all 64 days of the heating season. The continue lines represent the outdoor temperature and the dashed lines the waste-heat temperature. The daily consumptions are divided into four plots with different temperature ranges at the outlet of the heat pump condenser (Tc). From Figure 3, it can be seen as the electricity absorbed by the heat pump can vary between 72.6 and 80.7 %, while the network pump absorbs ca. 15.8 % of the substation's total electricity consumption. Auxiliaries account for 7.4 %.

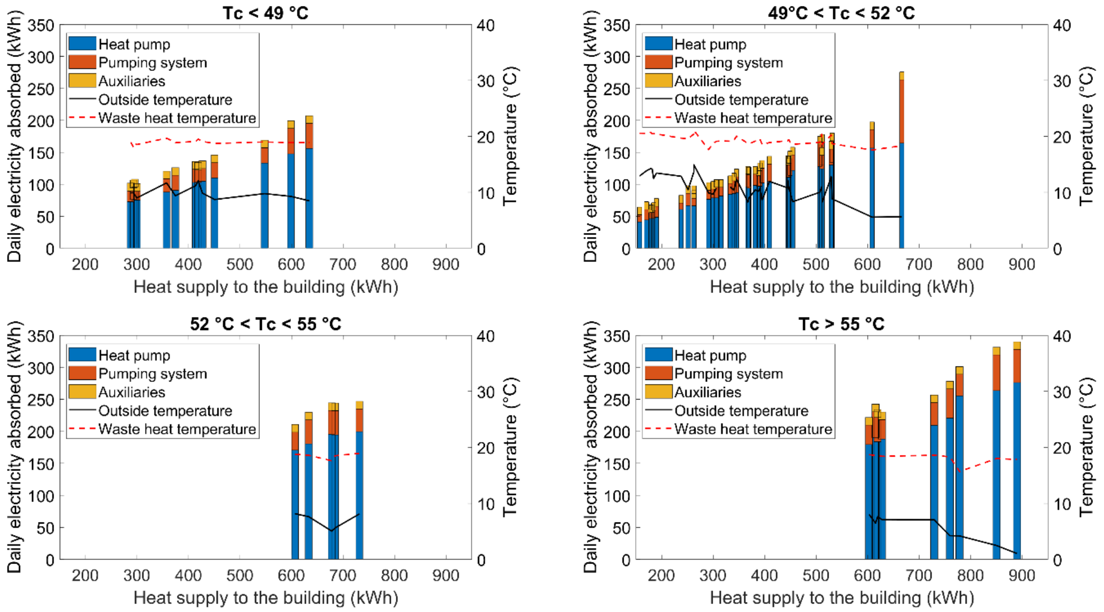

Figure 3. Energy consumption of the heat pump (blue), network pump (orange) and auxiliaries (yellow), with outside and waste heat temperatures. The four charts differ for the temperatures at the heat pump condenser.

The off-design tests have been carried out with temperatures at the evaporator inlet between 12 and 30 °C with increments of 2 °C, with the intention of increasing this range up to 40 °C in the coming months. On the other hand, the temperature range at the condenser is from 40 to 60 °C in steps of 5 °C.

These tests have been performed by keeping the heat pump under the test conditions for three hours. The data acquired during the three hours were filtered to retain only those values in which the heat pump was operating under steady-state conditions. The filter consists of disregarding *COP* values that deviate more than 3 % from the five minutes moving average, in order to disregard transient values due to the compressors switching on or off.

The results are presented through Figure 4, which describes the performance of the heat pump using the *COP* as key parameter index. The intention is to represent the *COP* as a function of the condenser temperature and the difference between condenser and evaporator temperature (ΔT_{lift}). Figure 4 shows the *COP* for different temperatures at the condenser outlet in different shades of colours. The COP value increases as the ΔT_{lift} decreases with a trend described by the centre of the crosses corresponding to the average *COP* value of the individual test. The vertical lines represent the standard deviation of the *COP*, the horizontal lines the standard deviation of ΔT_{lift}. The measurements that deviate from the main trend and the greatest value of the standard deviation of these are found when both heat pump compressors are running. When the two compressors are in operation, the increase in heat absorbed by the evaporator is achieved by decreasing the outlet temperature to the evaporator, while maintaining the same temperature at the inlet. In this way, the evaporation temperature decreases. The *COP* also increases by decreasing the condenser temperature, indeed, the measurement with the same ΔT_{lift} resulting in higher *COP* value with a lower condenser temperature.

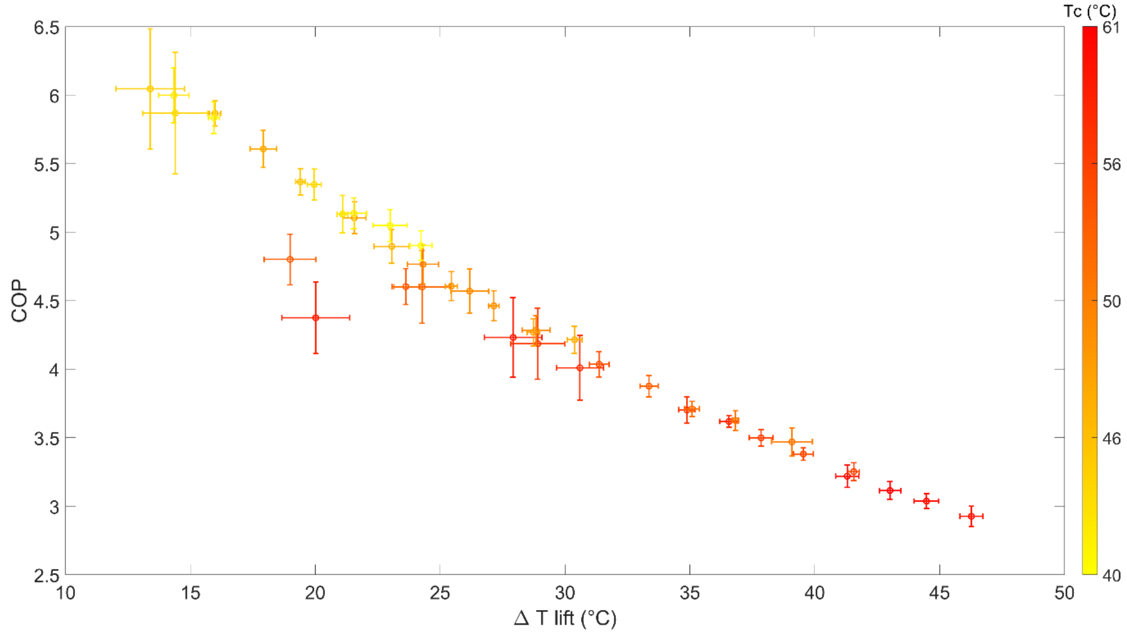

Figure 4. Performance of the heat pump for different temperatures at the condenser and evaporator.

The intention to study different temperature at the heat pump evaporator is due not only to the possibility of having different kinds of low-temperature heat sources, but also to the fact that temperatures within a 5GDH network may change over time depending on the heating or cooling demand of the end users connected to the grid. Therefore, it is useful to know the behaviour of the heat pump under different operating conditions. Lindhe et al. [7] explain that the heat pump for 5GDH network substation should have high performance for both heating and cooling configuration and for different operating points, not only under design conditions.

4. Conclusions

The aim of this work is to test a prototype substation for the 5GDH networks in a real case study. The substation covers the heating and cooling demand of a real building using low-temperature waste heat. This article describes the components, the substation layout and the 5GDH network that enables the prototype to recover the waste heat. The results show the energy consumption of the substation in heating configuration during the 2023-2024 heating season and the performance of the heat pump under design conditions. Moreover, the heat pump was tested under off-design conditions, which are obtained when the heat pump operates in a wider temperature range at the evaporator and condenser than in design condition.

The average value of the COP for the design tests is between the 3.3 and 4.2 maintaining 18 °C at the evaporator inlet, while the condenser temperature is between 49 and 59 °C. The GCOP has values between 2.6 and 3.1 considering the heat supply to the building and the overall energy consumption of the heat pump, pumps and auxiliaries.

The off-design tests show an average COP of 2.9 to 6.1 for different values of temperature difference between condenser and evaporator.

Future tests will be developed to analyse the performance of the substation in the cooling configuration in the summer of 2024. These results are useful for the techno-economic evaluation of the development of 5GDH networks. The data obtained from this work can therefore be used as input parameters in models studying the feasibility of this kind of networks.

References

[1] Eisentraut, Anselm, and Adam Brown. Heating Without Global Warming: Market Development and Policy Considerations for Renewable Heat: Featured Insight. OECD/IEA, 2014.
[2] Sadeghi, H., Jalali, R., & Singh, R. M. (2024). A review of borehole thermal energy storage and its integration into district heating systems. Renewable and Sustainable Energy Reviews, 192, 114236. https://doi.org/10.1016/J.RSER.2023.114236
[3] Lund, H.; Moller, B.; Mathiesen, B.; Dyrelund, A. The role of district heating in future renewable energy systems. Energy 2010, 35, 1381–1390.
[4] European Commission. An EU strategy on heating and cooling. J Chem Inf Model 2016;53(9):1689-99.https://energy.ec.europa.eu/topics/energy-efficiency/heating-and-cooling_en
[5] Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. In Energy (Vol. 68, pp. 1–11). Elsevier Ltd. https://doi.org/10.1016/j.energy.2014.02.089
[6] Saini, P., Huang, P., fiedler, F., Volkova, A., & Zhang, X. (2023). Techno-economic analysis of a 5th generation district heating system using thermo-hydraulic model: A multi-objective analysis for a case study in heating dominated climate. Energy and Buildings, 296, 113347. https://doi.org/10.1016/J.ENBUILD.2023.113347
[7] Lindhe, J., Larsson, M., Willis, M., Tiljander, P., & Johansson, D. (2024). Challenges and potentials of using a local heat pump in a 5 GDHC solution: Results from field and laboratory evaluations. Energy, 289, 129807. https://doi.org/10.1016/J.ENERGY.2023.129807
[8] García-Céspedes, J., Herms, I., Arnó, G., & de Felipe, J. J. (2023). Fifth-Generation District Heating and Cooling Networks Based on Shallow Geothermal Energy: A review and Possible Solutions for Mediterranean Europe. In Energies (Vol. 16, Issue 1). MDPI. https://doi.org/10.3390/en16010147
[9] Buffa, S., Cozzini, M., D'Antoni, M., Baratieri, M., & Fedrizzi, R. (2019). 5th generation district heating and cooling systems: A review of existing cases in Europe. In Renewable and Sustainable Energy Reviews (Vol. 104, pp. 504–522). Elsevier Ltd. https://doi.org/10.1016/j.rser.2018.12.059
[10] Reiners, T., Gross, M., Altieri, L., Wagner, H. J., & Bertsch, V. (2021). Heat pump efficiency in fifth generation ultra-low temperature district heating networks using a wastewater heat source. Energy, 236. https://doi.org/10.1016/j.energy.2021.121318.
[11] Martinazzoli, G.; Pasinelli, D.; Lezzi, A.M.; Pilotelli, M. Design of a 5th Generation District Heating Substation Prototype for a Real Case Study. Sustainability 2023, 15, 2972. https://doi.org/10.3390/su15042972

Acknowledgments

The authors thank the other people who are working on the development of the substation prototype.

Funding

This research was funded by MUR, fund PON "Ricerca e Innovazione" 2014–2020, Azione IV.4 "Dottorati e contratti di ricerca su tematiche dell'innovazione" and Azione IV.5 "Dottorati su tematiche green".